

Top at Twenty

Searches for new physics in the Top Sector at the LHC

Davide Gerbaudo

UC Irvine

On behalf of the CMS and ATLAS collaborations



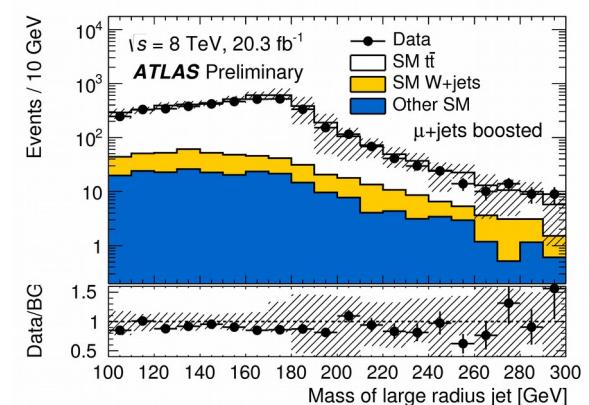
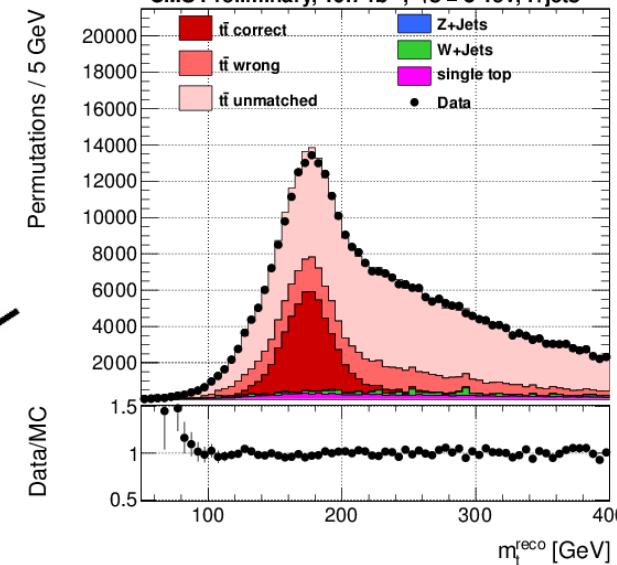
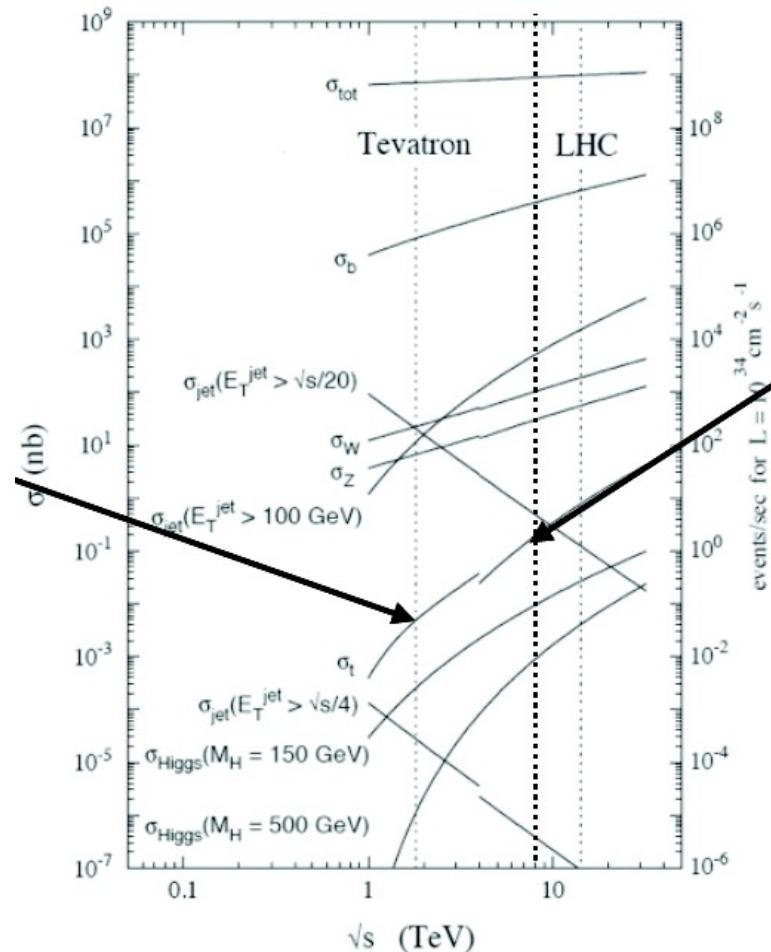
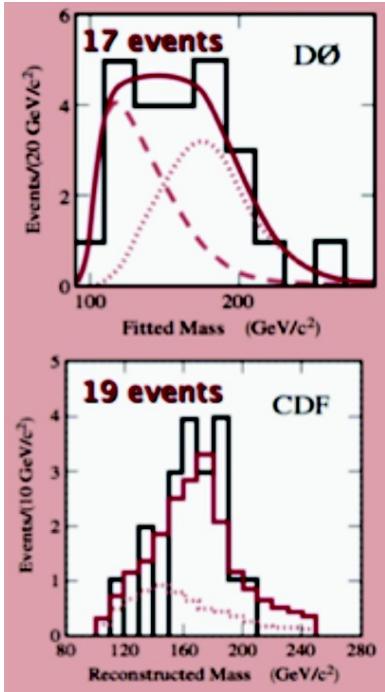
Fermilab, April 2015



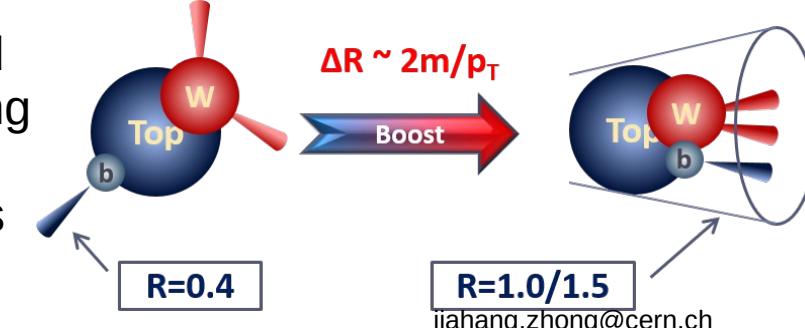
20 Years Collecting Top Quarks



1995



LHC top searches and measurements entering the TeV-scale
→ **Boosted** top quarks



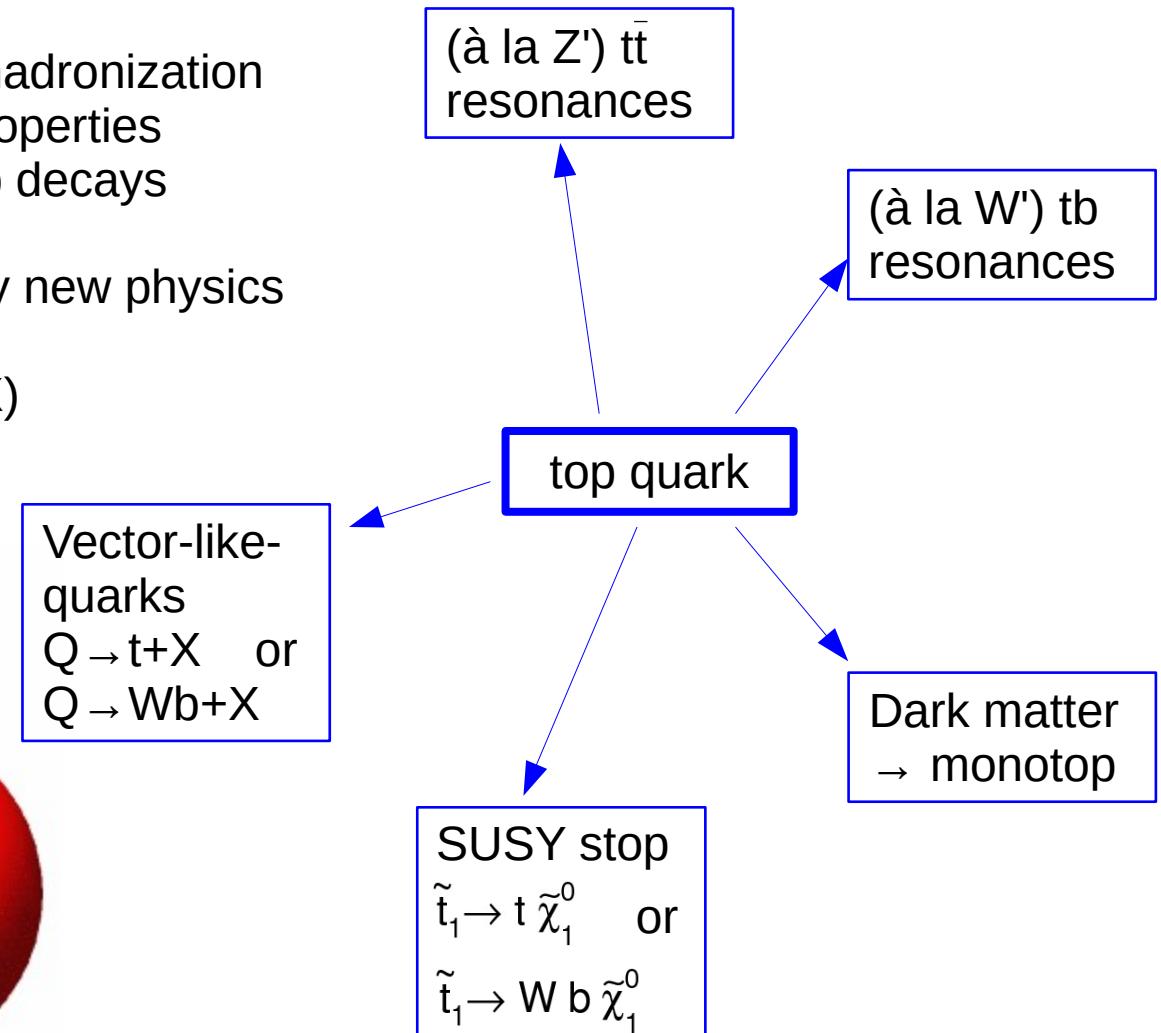
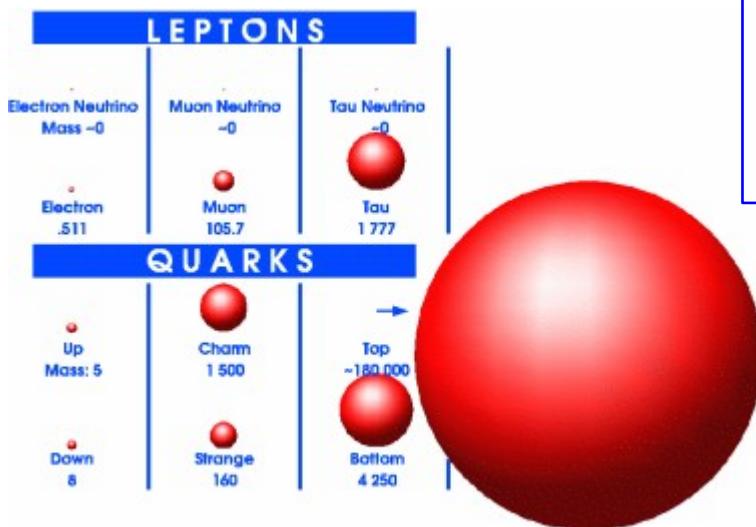
Efficient hadronic top-tagging:

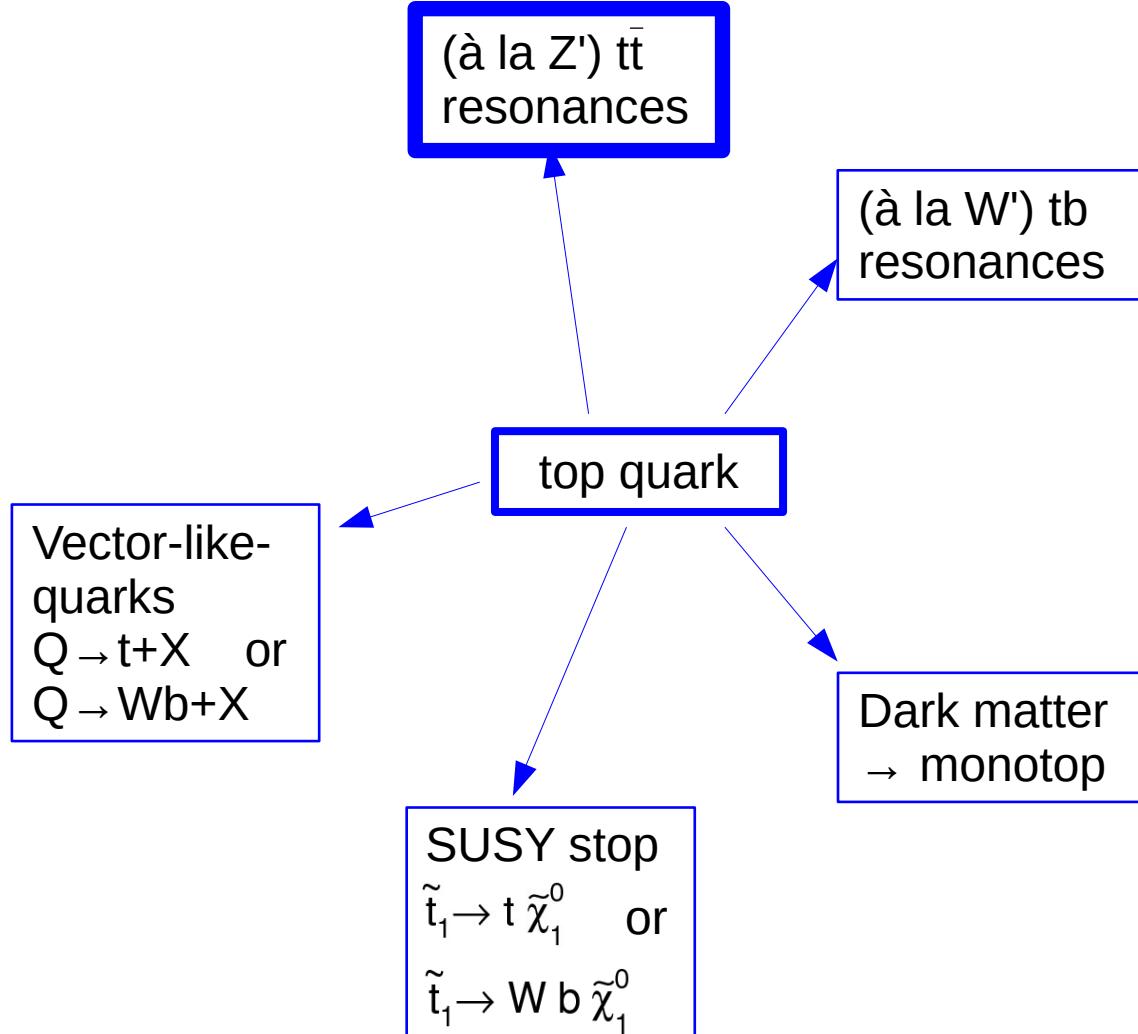
- large R** jet as top candidate, less combinatorics
- jet **substructure** can be exploited for powerful discriminants

Top Quark and New Physics

Several reasons for which final states containing top quarks are an excellent means to probe new physics:

- the **top quark decays** before hadronization
 - direct studies of top-quark properties
 - search for new physics in top decays
- the **top quark is heavy**
 - it plays a special role in many new physics models
 - large BR(heavy particle $\rightarrow t+X$)







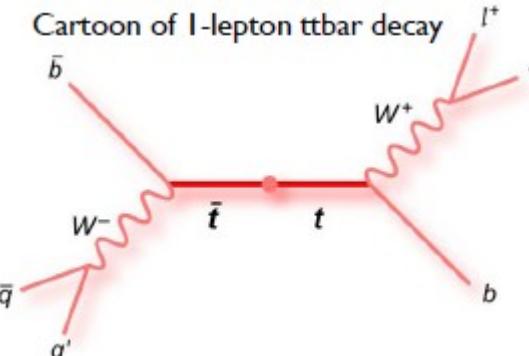
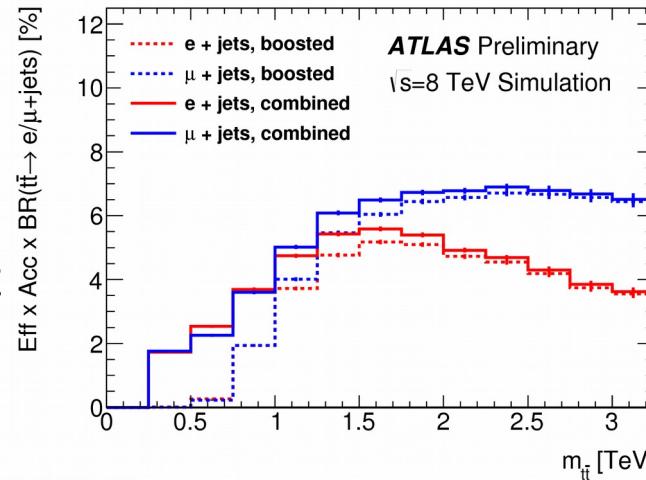
ATLAS: $t\bar{t}$ resonances in $\ell+jets$

ATLAS-CONF-2015-009 New!

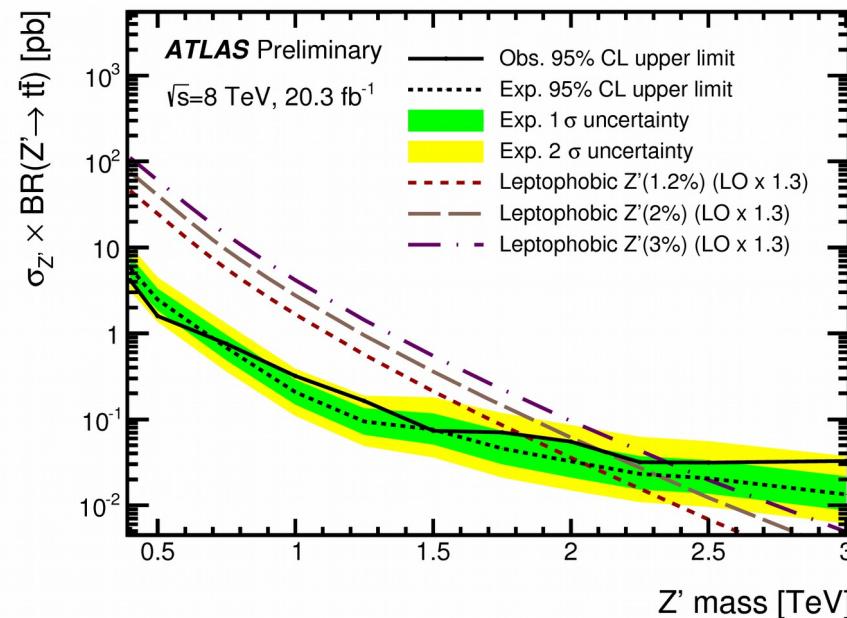
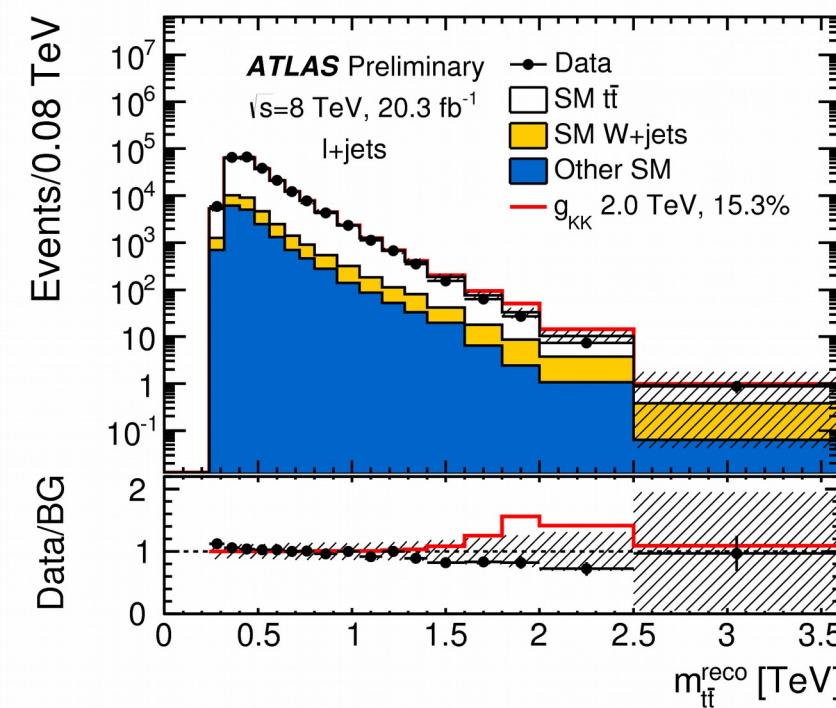


Resolved + boosted selections:

- Resolved: $t\bar{t}$ with $\ell+u+4$ small R jets; choose kinematically best combination
- Boosted:
 - **leptonic top** = $\ell+u+small\ R\ jet$
 - **hadronic top** = large R jet with high mass, hard substructure



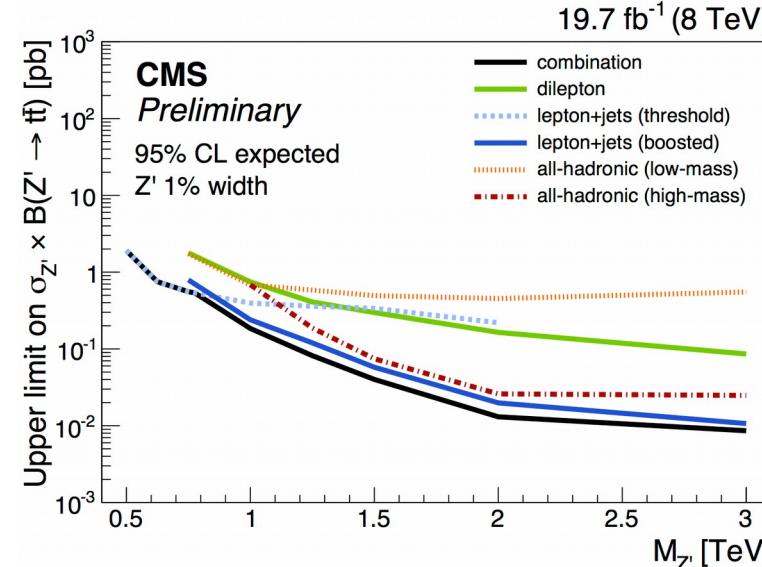
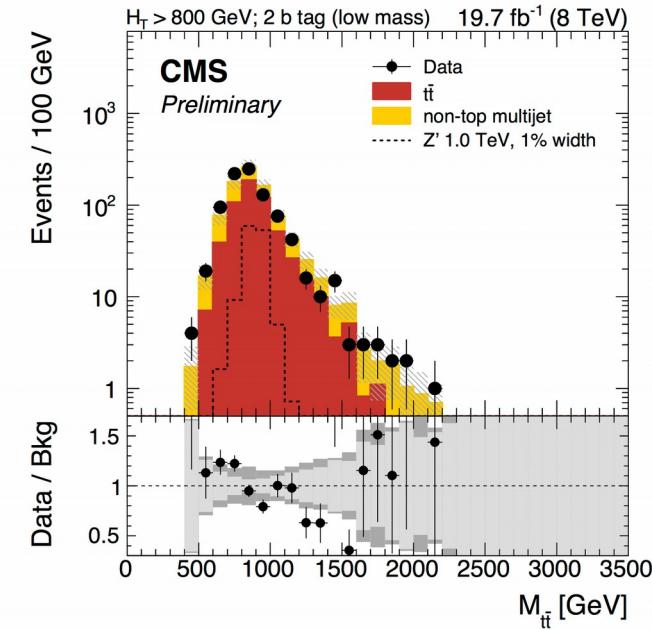
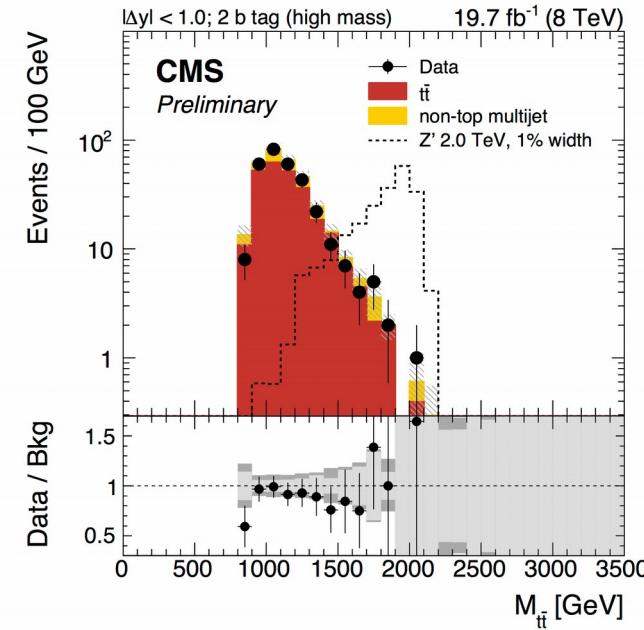
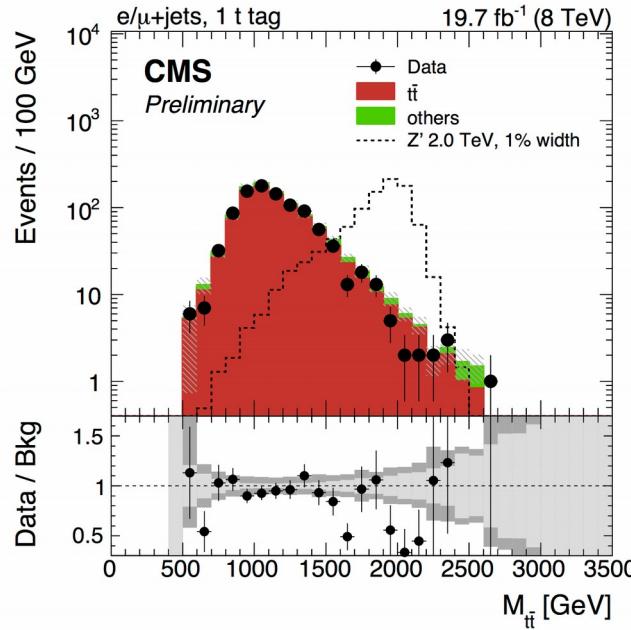
- Wide mass range covered
- Resolution $\sim 10\%$
- Narrow leptophobic Z' excluded up to 1.8TeV





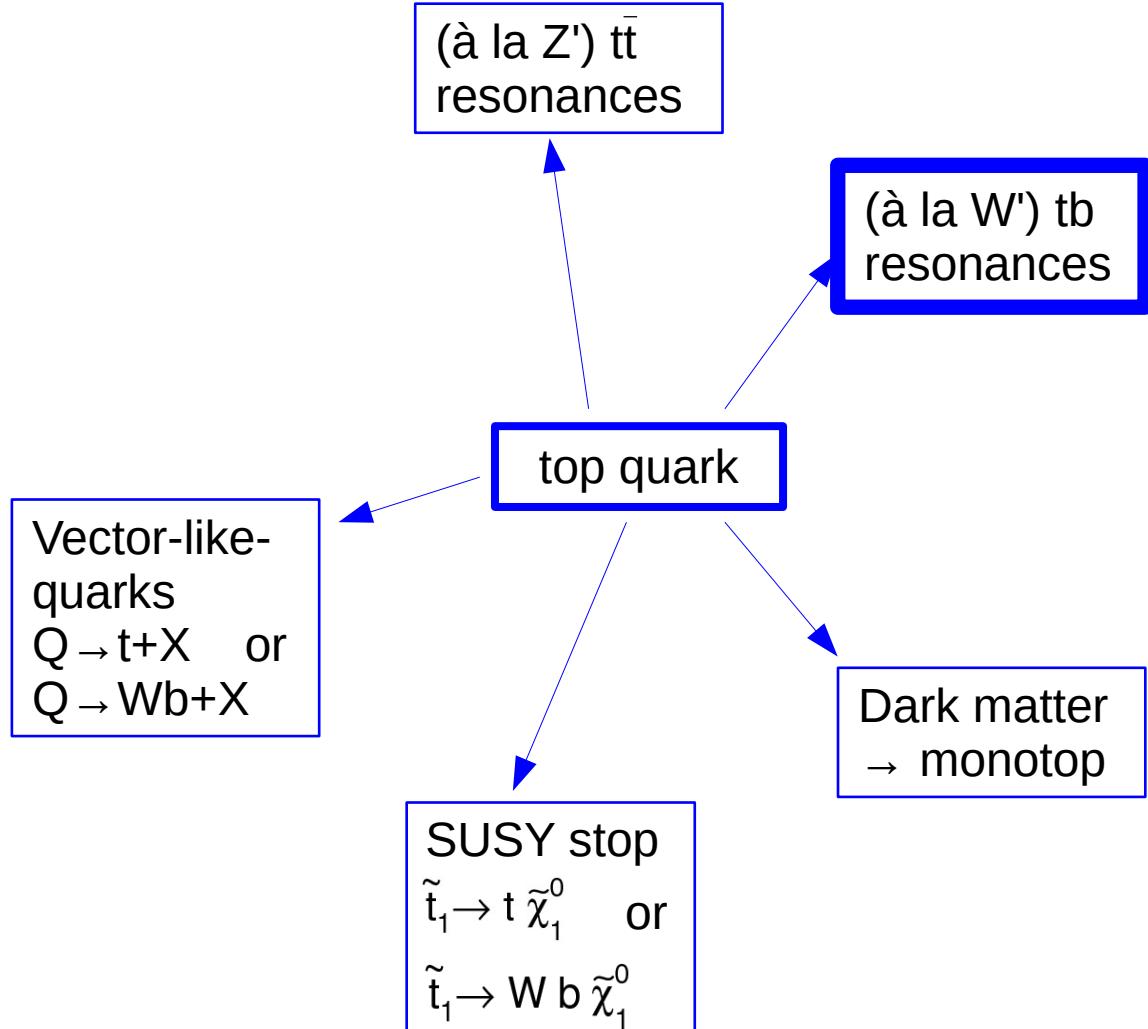
CMS: $t\bar{t}$ resonances in all final states

CMS B2G-13-008 New!



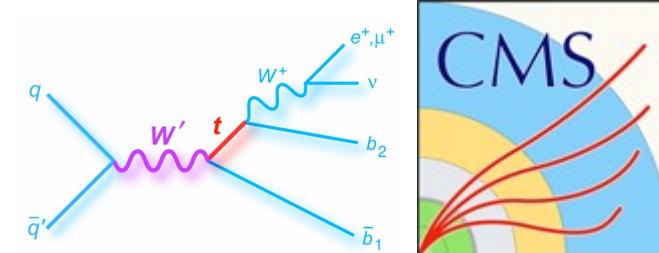
Optimized for boosted tops, using jet substructure.
Consider all three possible top-pair decays:

signal hypothesis	mass limit [TeV]						combined	combined
	dilepton channel		lepton+jets channel		all-hadronic channels			
	obs.	exp.	obs.	exp.	obs.	exp.	obs.	exp.
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	1.5	1.4	2.3	2.2	2.1	2.1	2.4	2.4
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.2	2.1	2.8	2.7	2.5	2.5	2.9	2.8
RS KK gluon	2.0	1.8	2.5	2.5	2.3	2.4	2.8	2.7



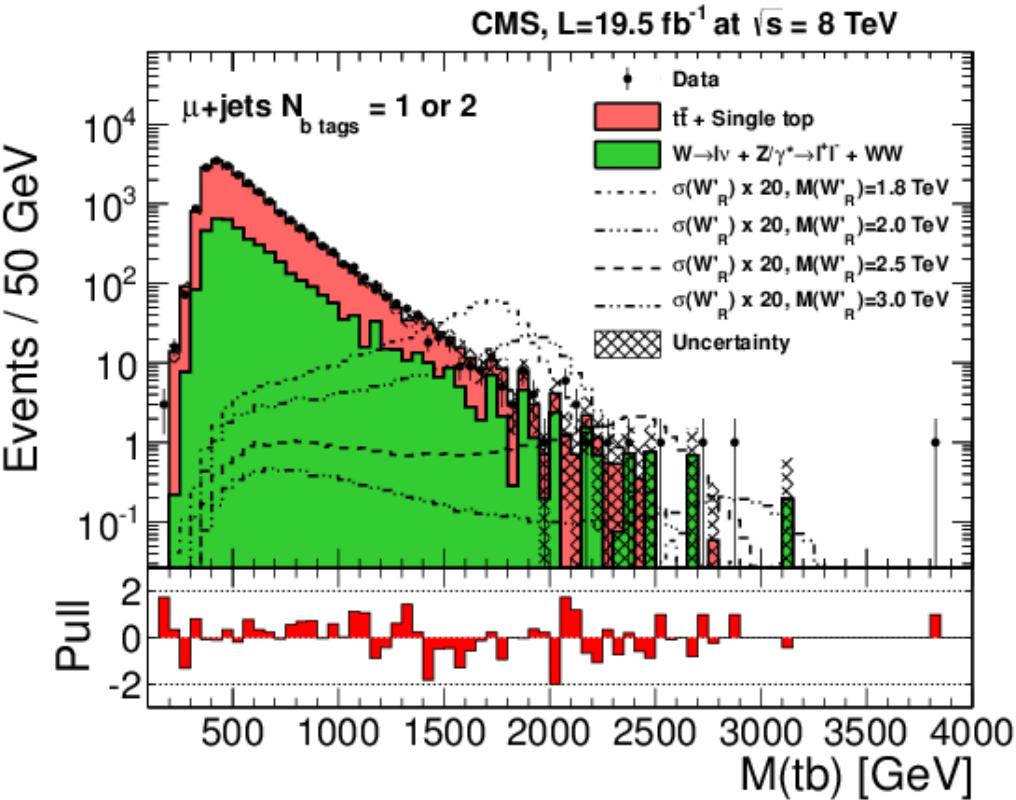


CMS: $W' \rightarrow tb$



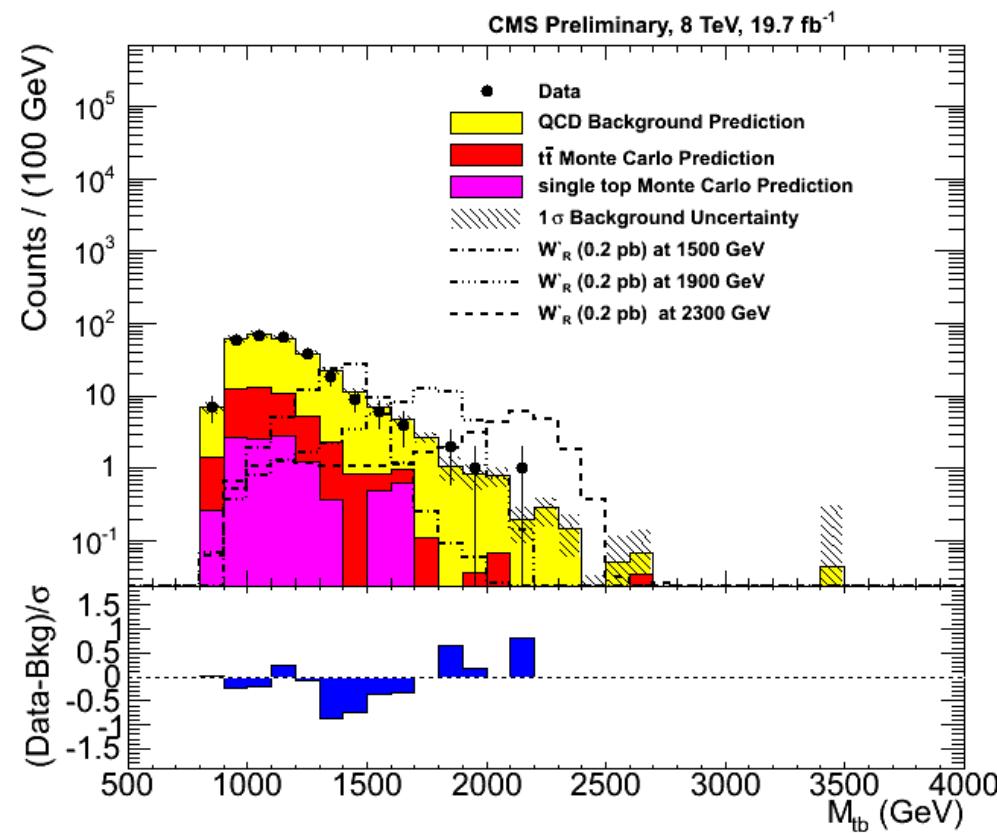
- **Single lepton** (e/μ) final state
- Missing E_T
- ≥ 2 jets (small-R), at least 1 b-tag
- top p_T reweighting derived in control region
- Exclude W'_R up to 2.03 TeV

JHEP 05 (2014) 108



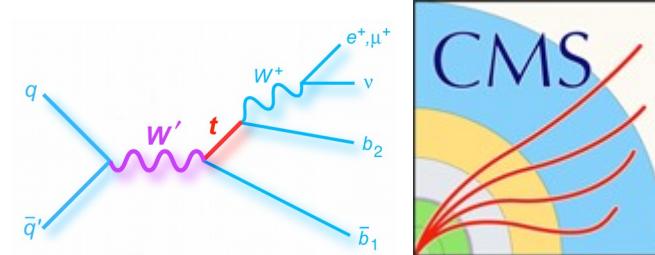
- **All-hadronic** final state
- Focus on di-jet topology, with one b-jet and one large-R top-jet (substructure)
- Exclude W'_R up to 2.0 TeV

PAS B2G-12-009





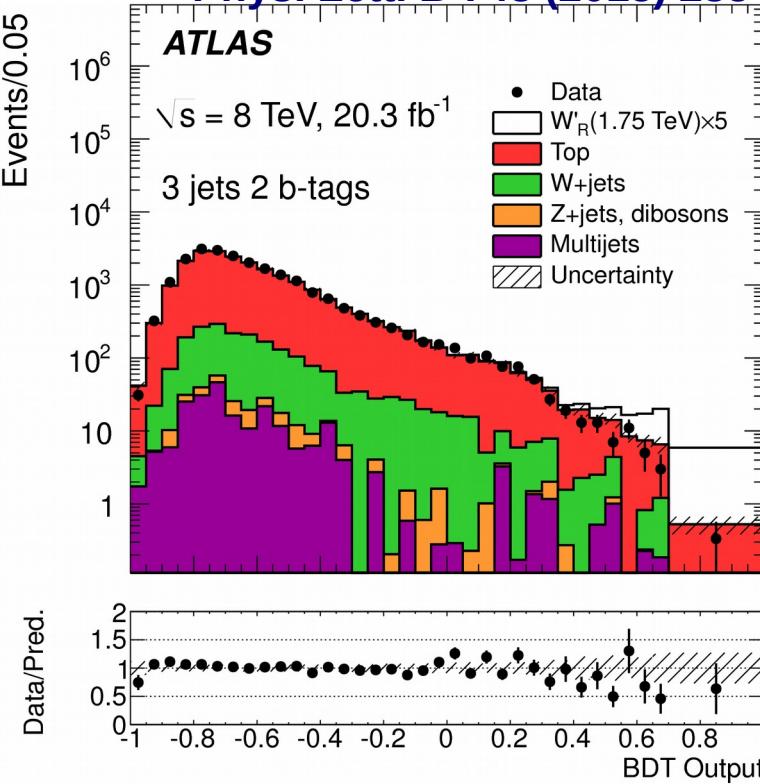
ATLAS: $W' \rightarrow tb$



Single-lepton (e/μ) final state

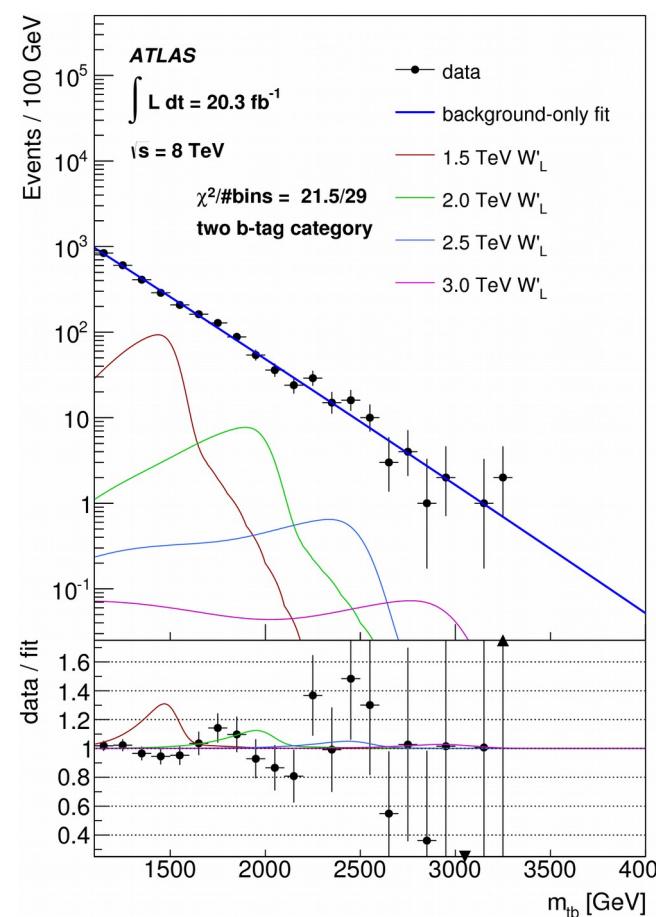
- Missing E_T
- 2 or 3 jets (small-R), 2 b-tags
- BDT discriminant, inputs:
 - $m(tb)$, $p_T(t)$, etc.
- Exclude W'_R (W'_L) as heavy as 1.92 (1.80) TeV

Phys. Lett. B 743 (2015) 235



All hadronic final state, two jets with $\Delta R > 2.0$

- One b-tagged $R=0.4$ jet, one $R=1.0$ **t-tag** jet,
- Two categories based on b-tag of top candidate
- jet substructure, N-subjettiness

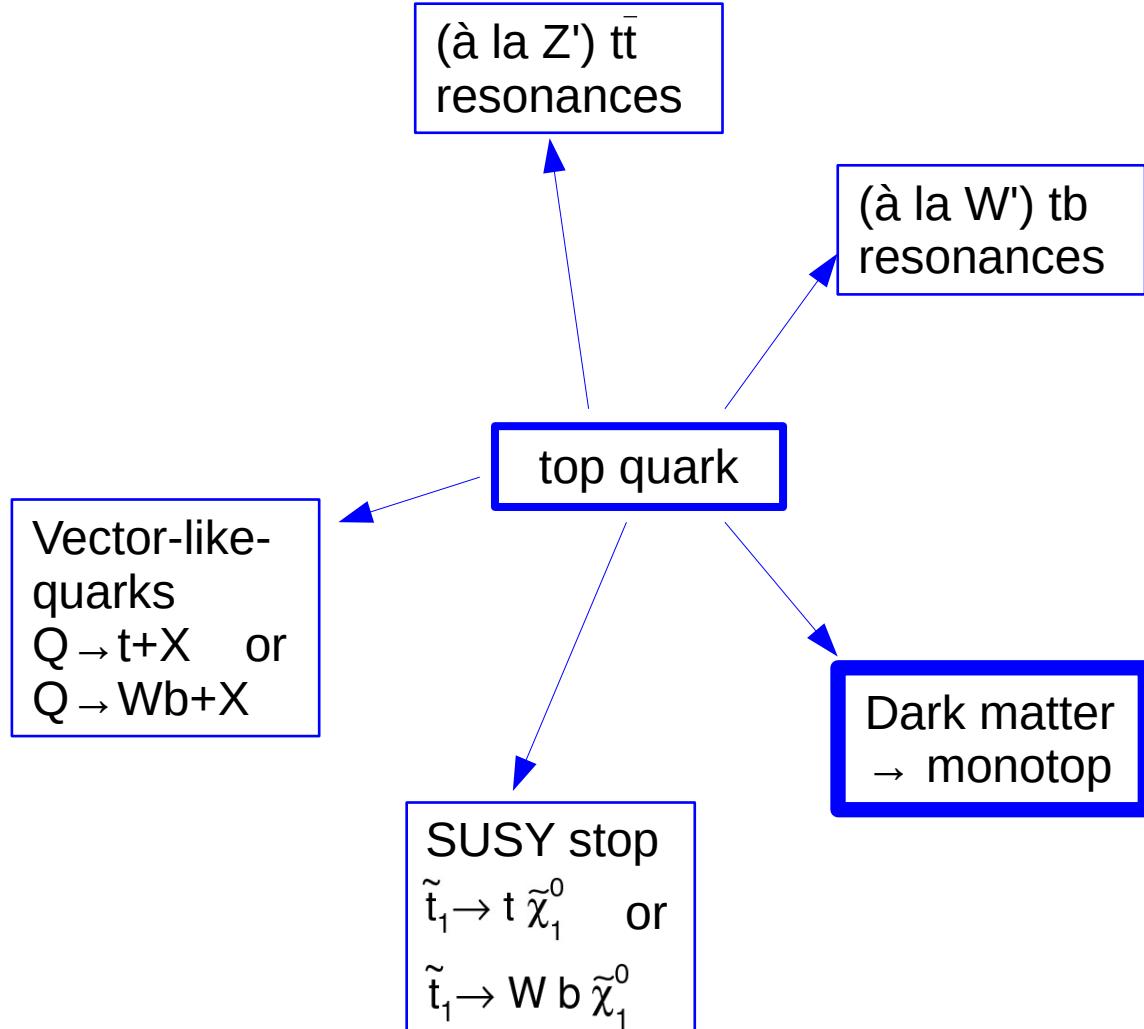


- Unbinned likelihood fit on $m(tb)$
- Bkg estimation from data

Exclude:

- W'_L up to 1.68 TeV
- W'_R up to 1.76 TeV

1408.0886 [hep-ex]
Submitted to EPJC



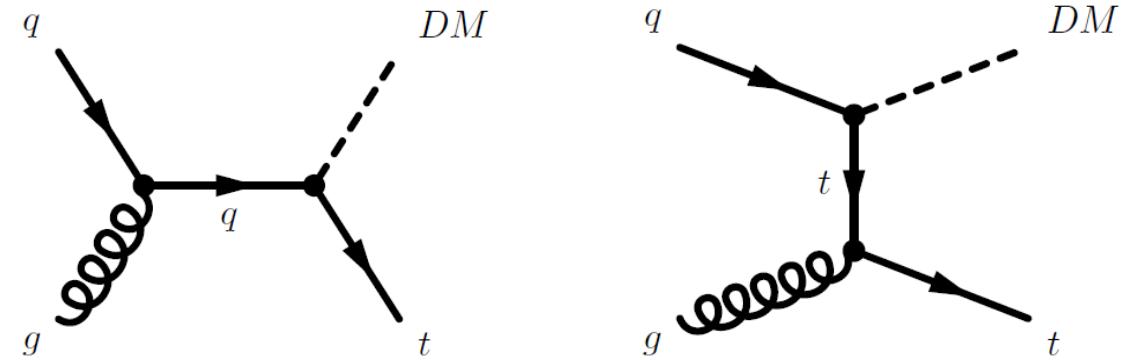


CMS: all-hadronic monotop



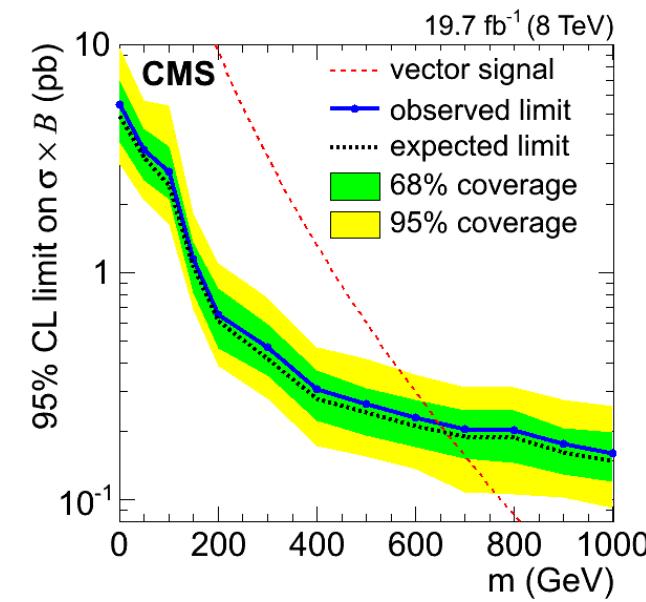
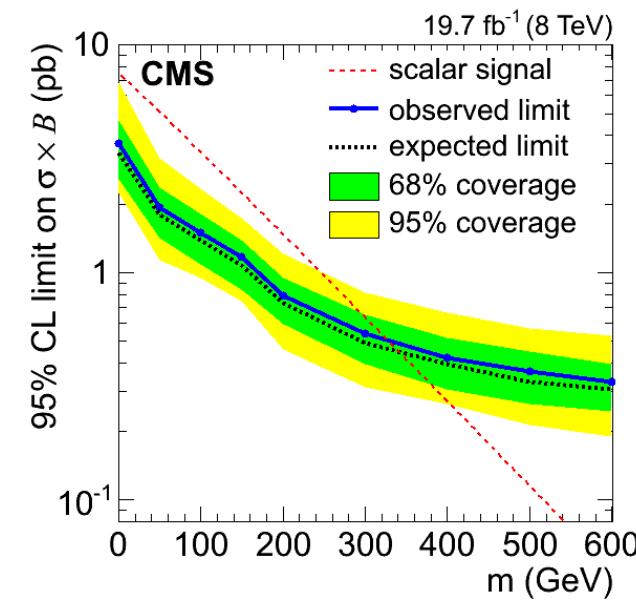
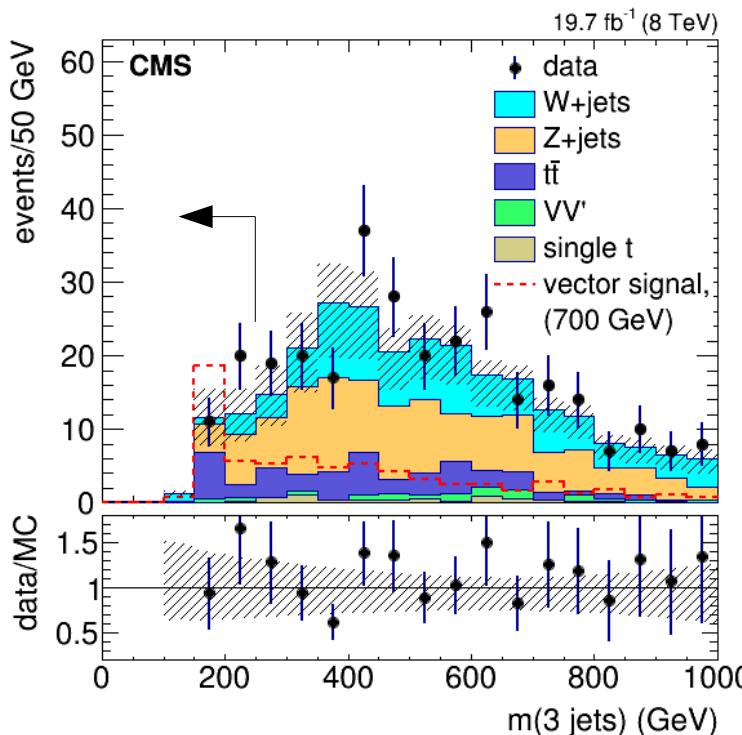
WIMP probe complementary to monojet and monophoton DM searches

- Large missing E_T
- Three high- p_T jets
- One b-tag
- Exclusion up to
 - 350 GeV (scalar)
 - 630 GeV (vector)



CMS B2G-12-022

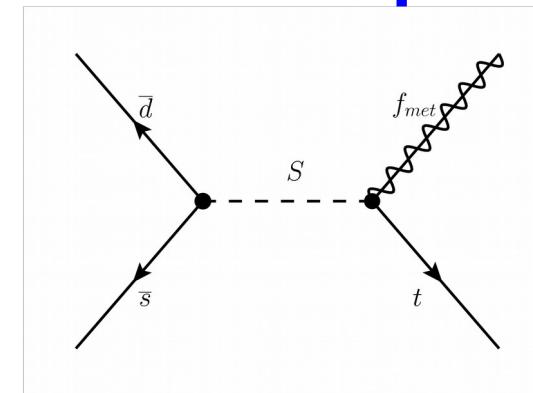
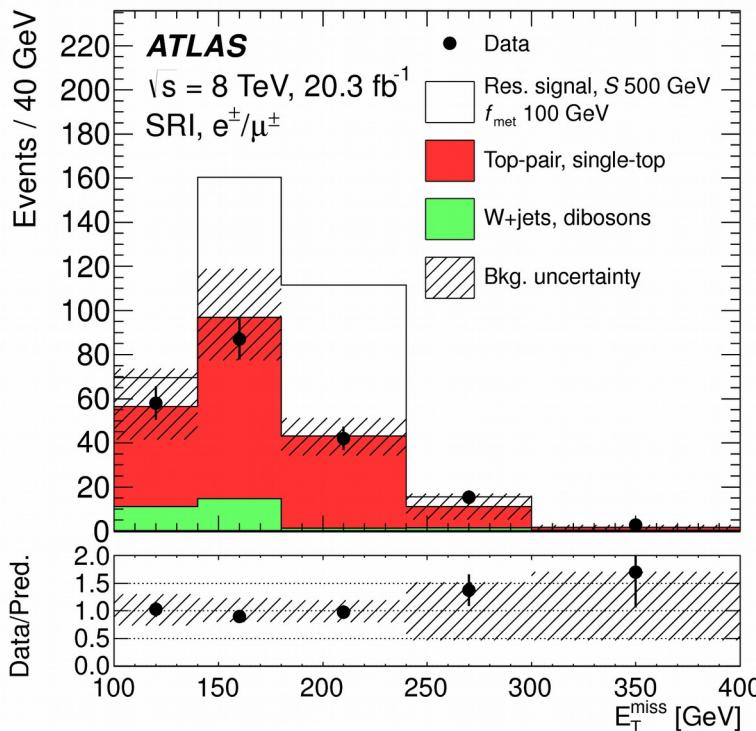
Phys. Rev. Lett. 114 (2015) 101801



ATLAS: $\ell + \text{jets}$ monotop

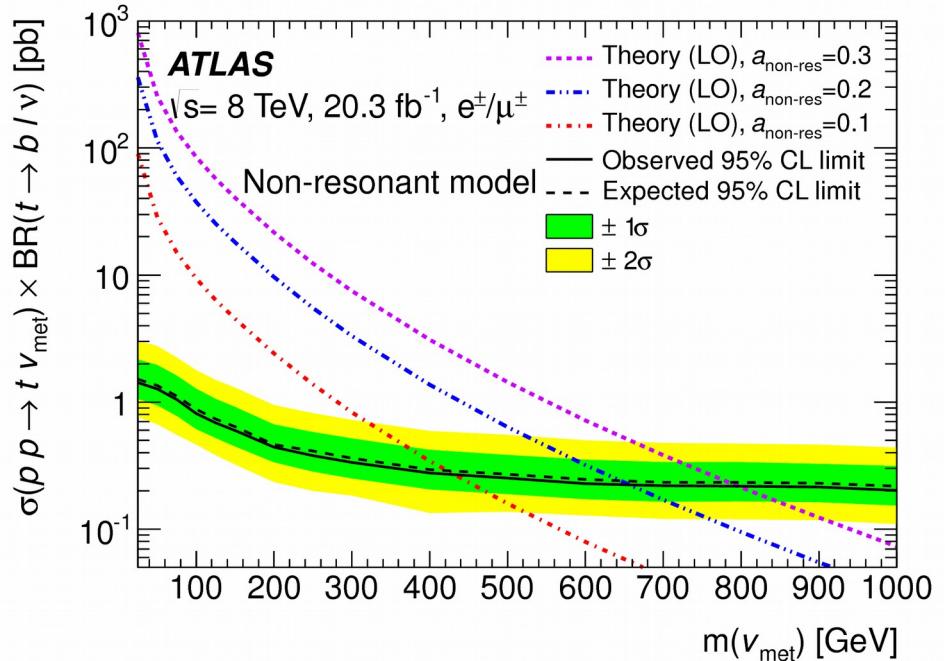
- $t \rightarrow Wb$ ($W \rightarrow \ell\nu$) + missing E_T
- $t\bar{t}$ (\rightarrow dilepton) is the main background
- $m_T(\ell, \text{missing } E_T)$ and $\Delta\Phi(\ell, b)$ are the main discriminating variables

Eur. Phys. J. C (2015) 75:79



Interpretation: many theories predicting monotop \rightarrow use effective models:

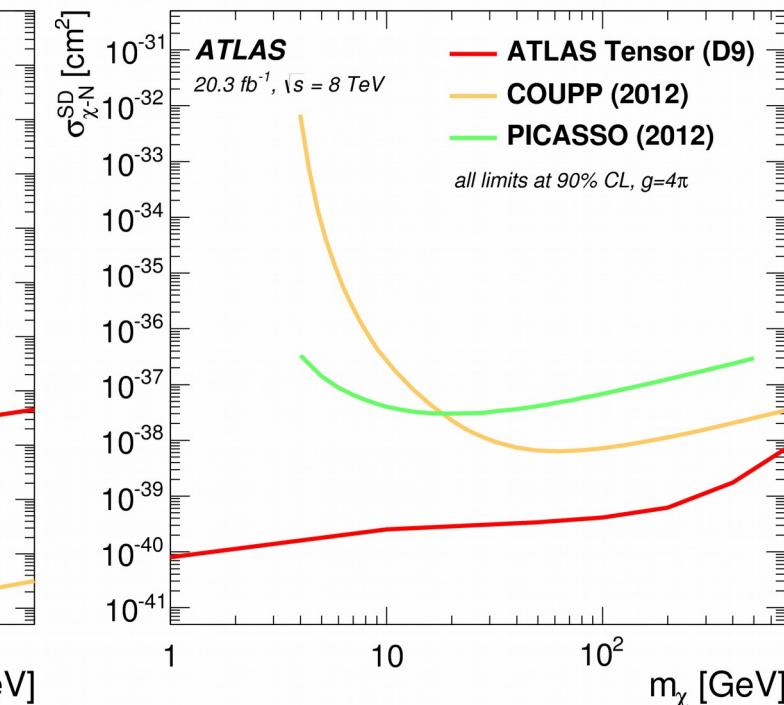
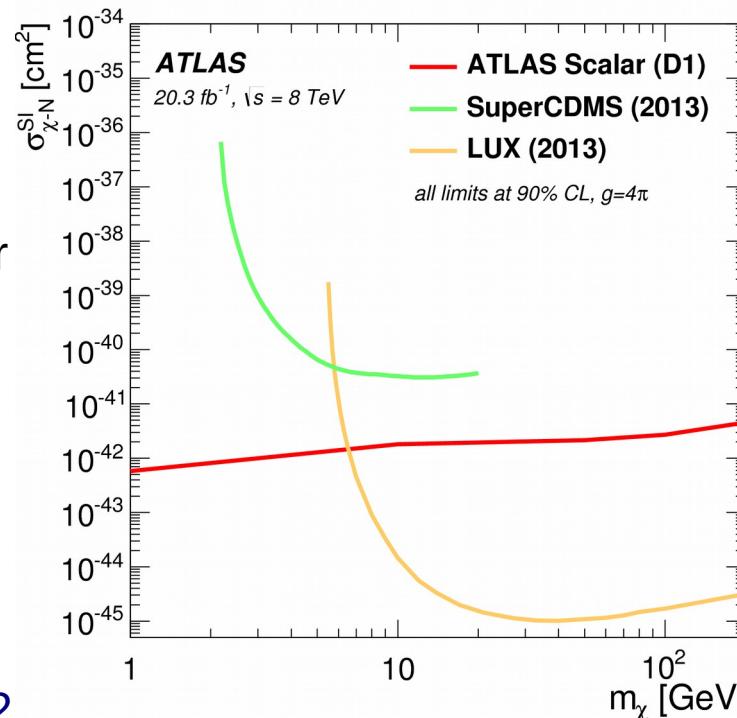
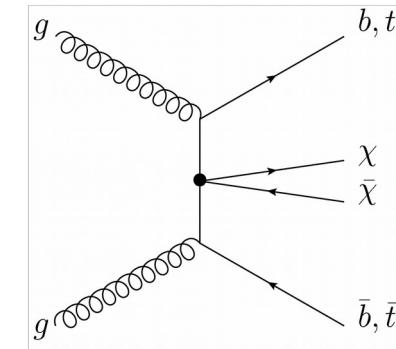
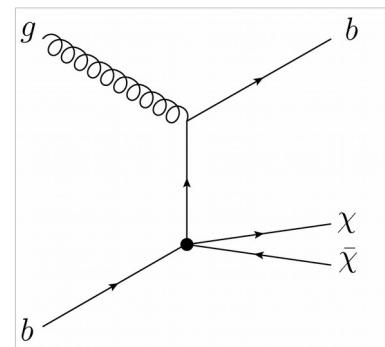
- resonant production of spin-0 $\rightarrow t_R f_{1/2}$
- non-resonant production of spin-1 + t_R



ATLAS: Dark Matter + HF

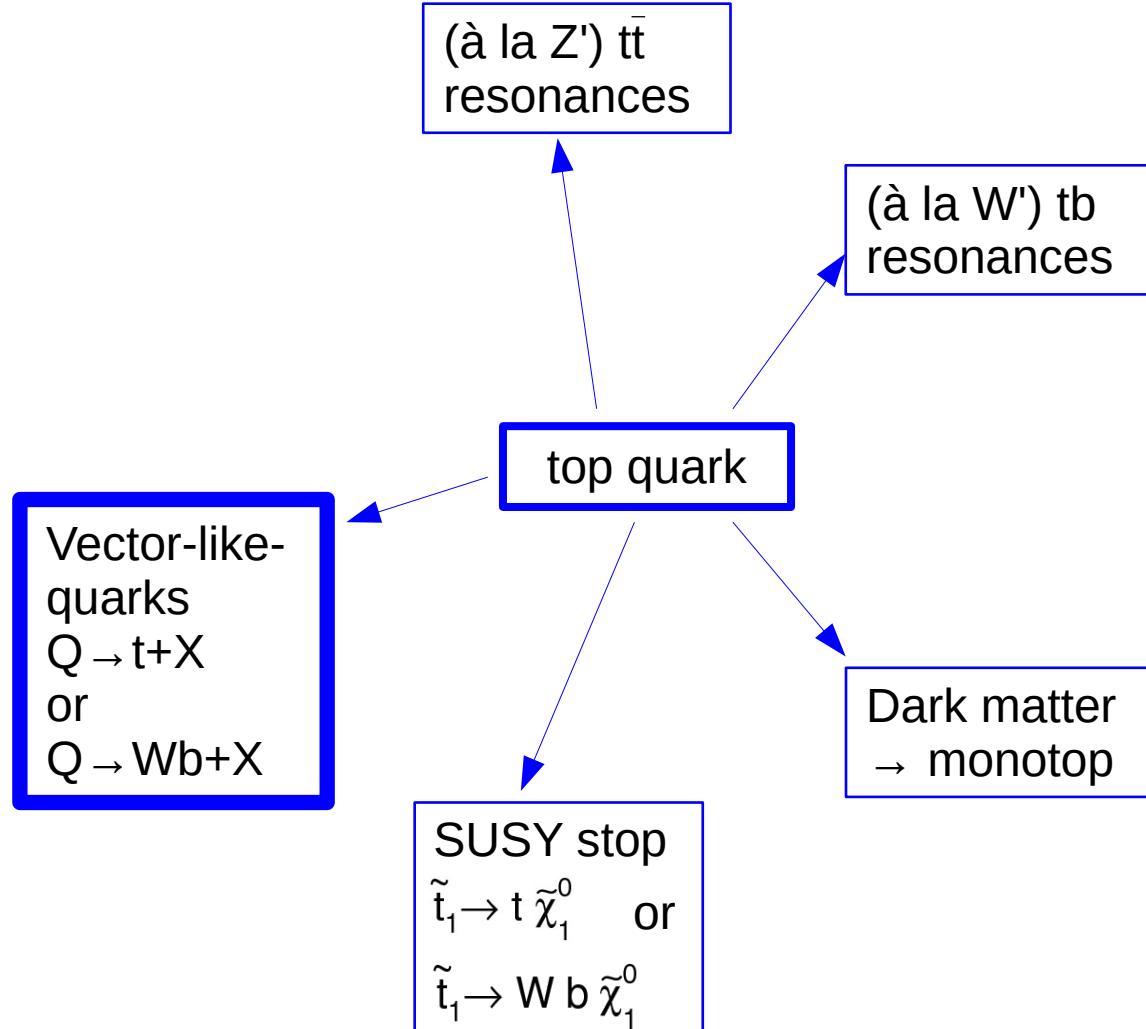
Dark matter pair production with t or b:

- large missing E_T
- at least one high- p_T jet
- four selections:
 - one or two b-jets
 - two top quarks, both with hadronic decays or one hadronic and one leptonic
- optimized selection with several advanced variables: razor, am_{T2} , topness



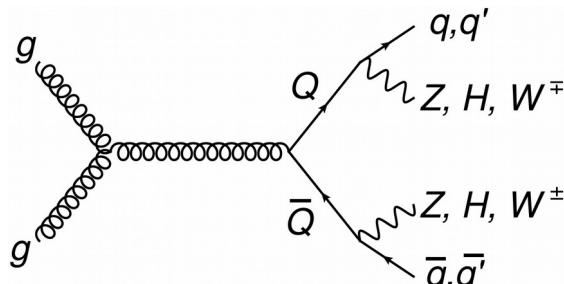
Eur. Phys. J. C (2015) 75:92

Strong limits in the **low mass region**, relevant to recent claims by DAMA/LIBRA, COGENT, CDMS, Fermi-LAT

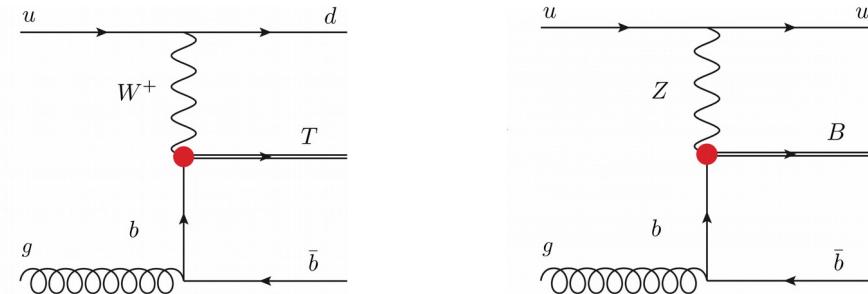


VLQ production and decay

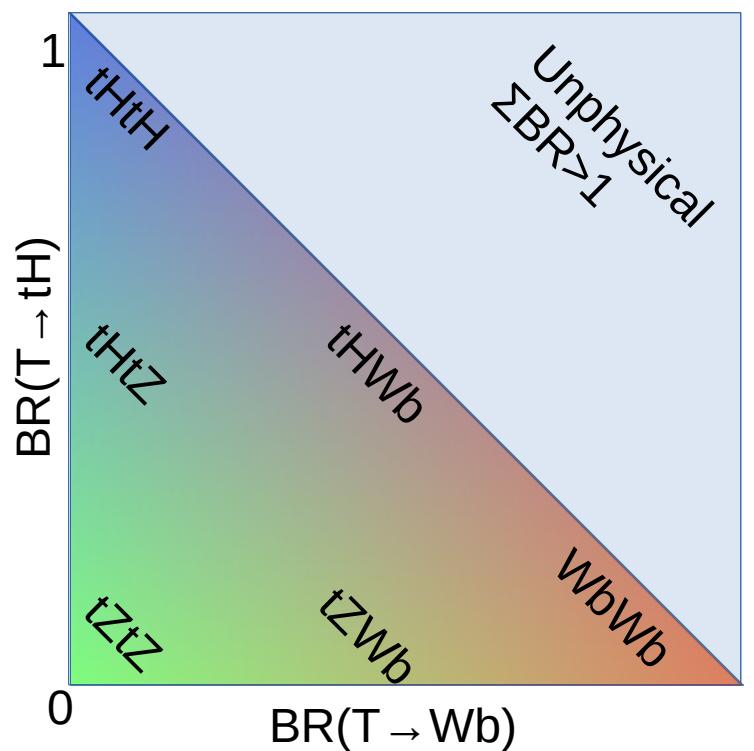
Pair Production



Single Production



Possible final states for $T\bar{T}$



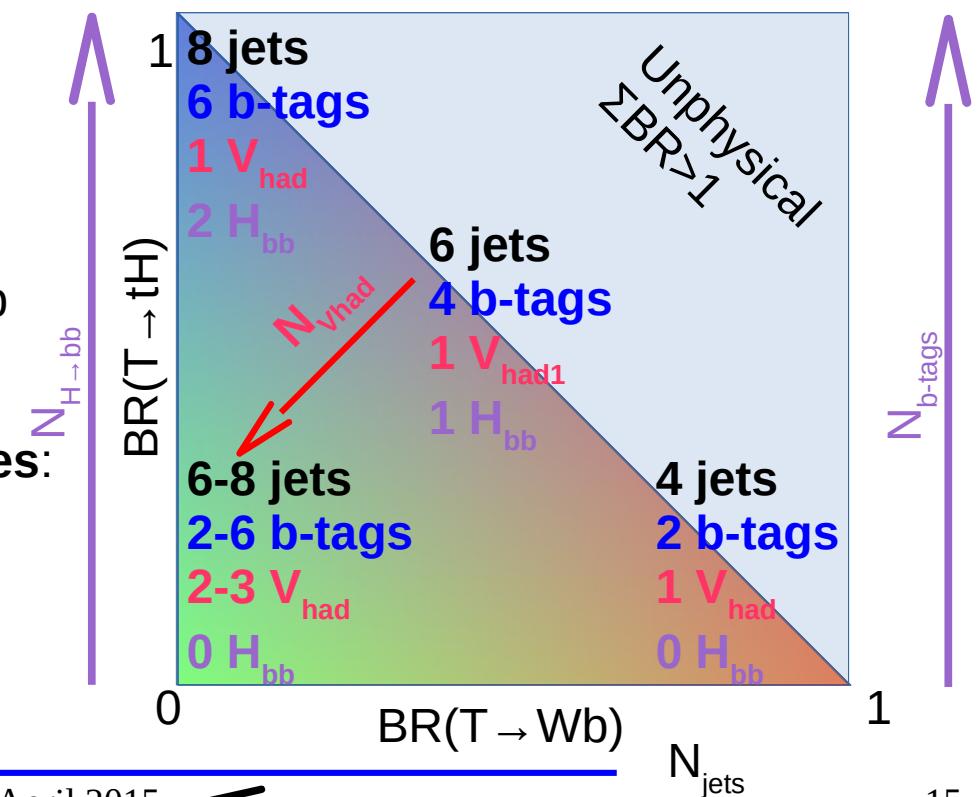
Decays:

- $T \rightarrow Wb/Zt/Ht$
- $B \rightarrow Wt/Zb/Hb$

Rich signatures:

- top quarks
- b jets
- $V_{had} \rightarrow jj/J$
- $H \rightarrow bb$.

Possible signatures for $T\bar{T}$ ($\ell + \text{jets}$)

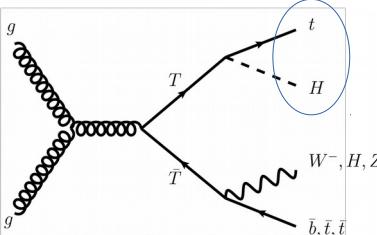




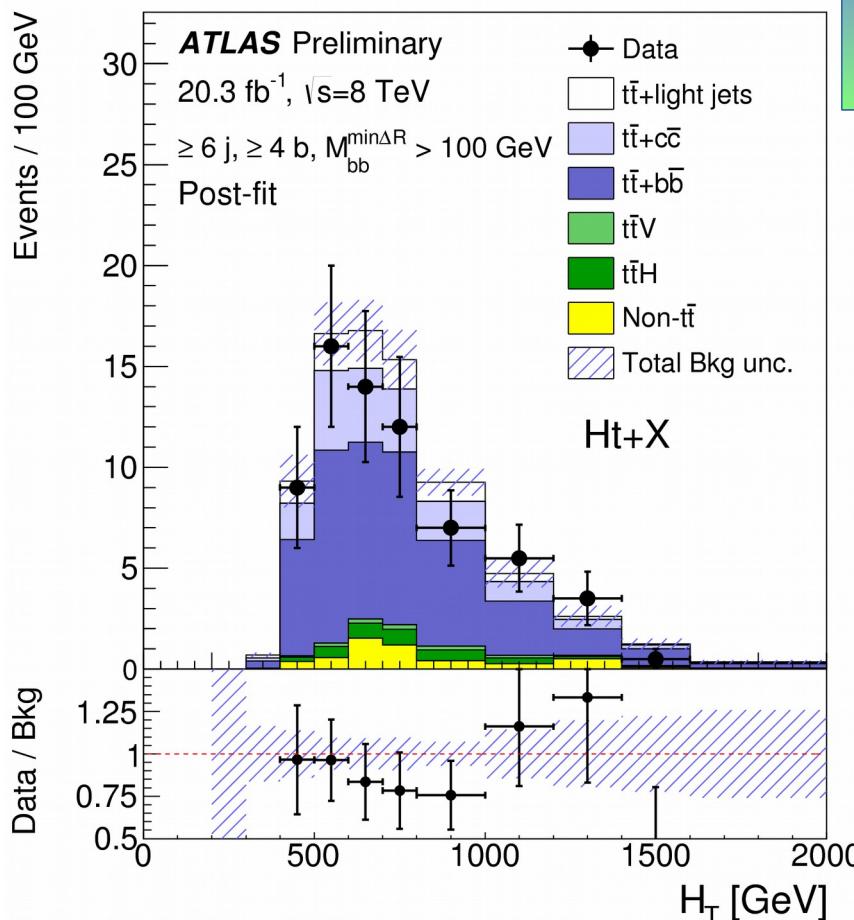
ATLAS: VLT

New! Ht+X

- dominant $H \rightarrow bb$
- $N_{jet} \geq 5, N_{b-jet} \geq 2$
- 8 channels, largest s/b for $N_{jet} \geq 6, N_{b-jet} \geq 4$



ATLAS-CONF-2015-012

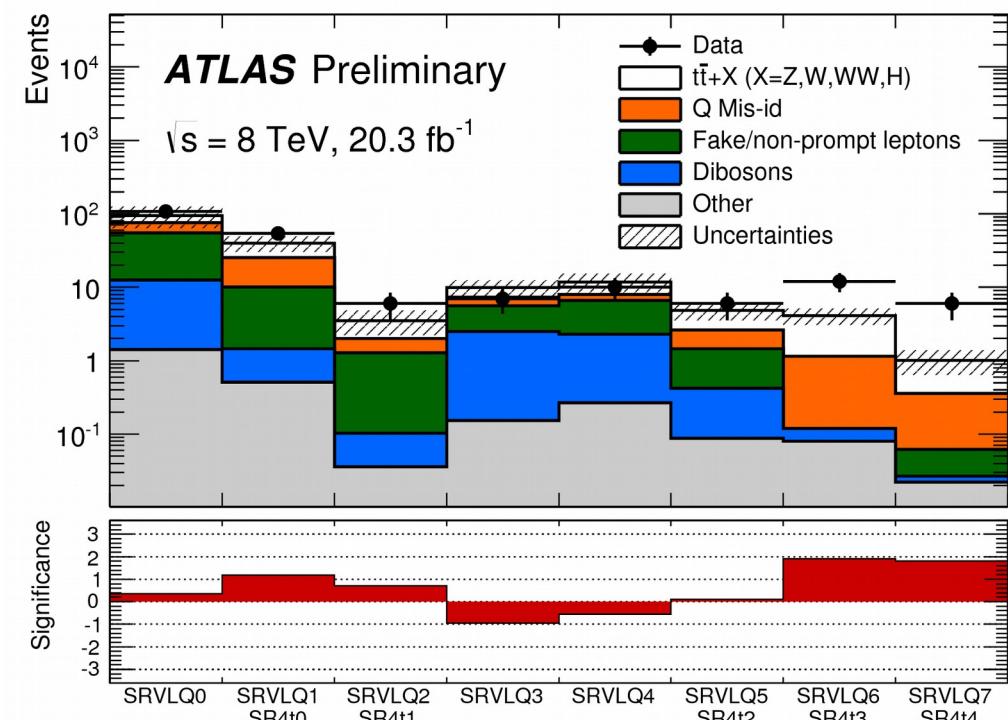


New!

Same-sign dilepton/trilepton (+ b-jets)

- SS 2ℓ or 3ℓ , $N_{b-jet} \geq 1$, missing E_T , H_T
- sensitive to VLQ and several other BSM models
- 11 SR based on charge, H_T , N_{b-jets} , missing E_T

CERN-PH-EP-2015-060





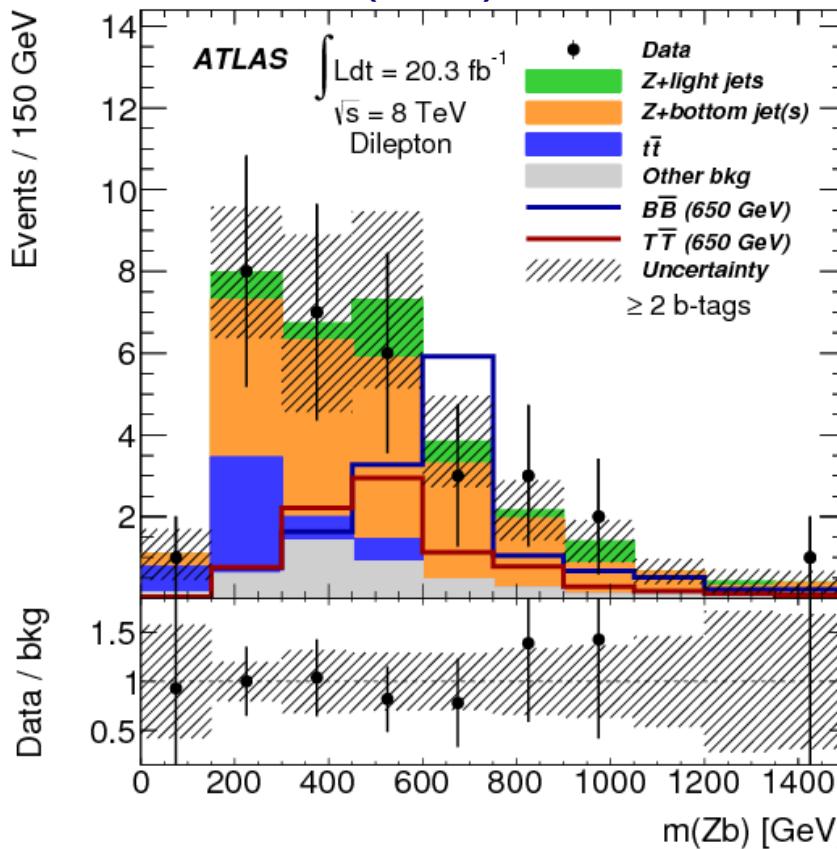
ATLAS: VLT



$T\bar{T} \rightarrow Zt + X$:

- $\ell\ell$ consistent with a high- p_T Z , allow 3rd ℓ
- $N_{\text{jet}} > 2$, $N_{\text{b-jets}} > 1$
- selections optimized on N_ℓ , $N_{\text{b-jets}}$, $N_{\text{fwd-jets}}$
- discriminant m_{Zb} or H_T

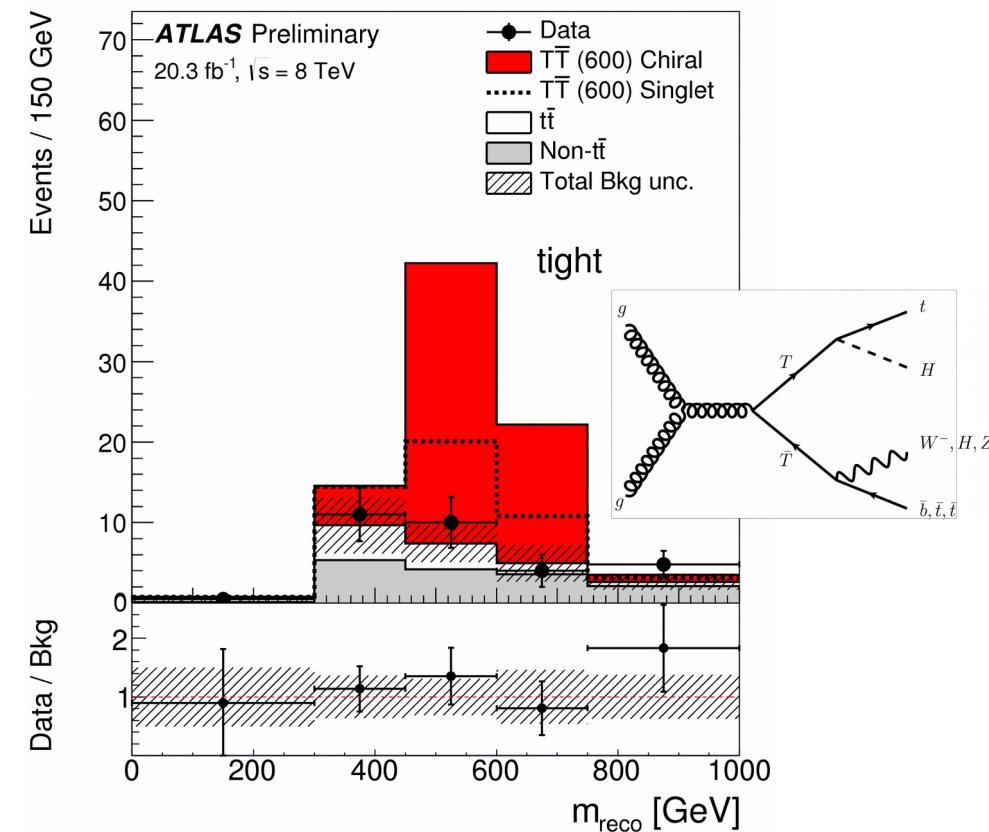
JHEP 11 (2014) 104



Wb+X **New!**

- optimized for $T\bar{T} \rightarrow WbWb$
- one $W \rightarrow \ell\nu$
- one W_{had} , boosted or resolved
- kinematic req. to suppress $t\bar{t}$

ATLAS-CONF-2015-012



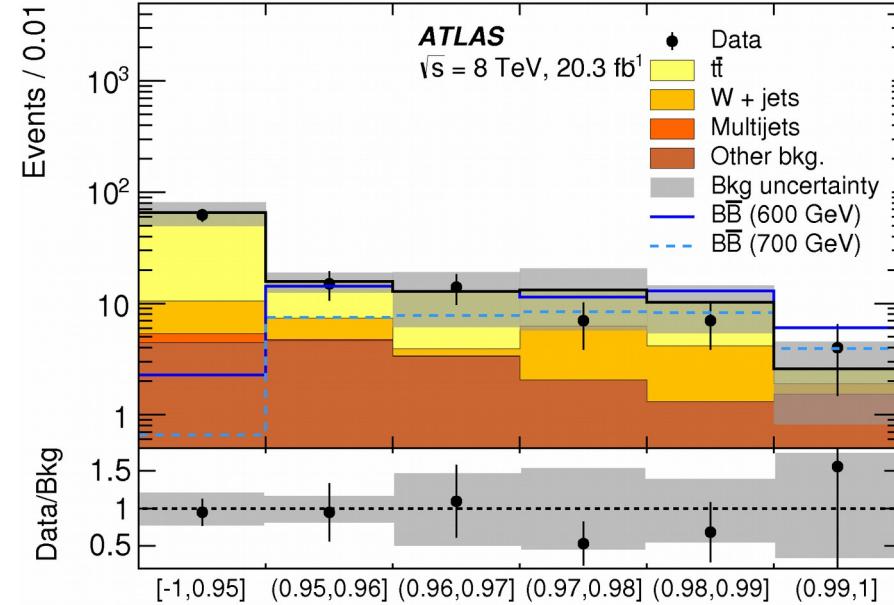


ATLAS: VLB in $\ell + \text{jets}$

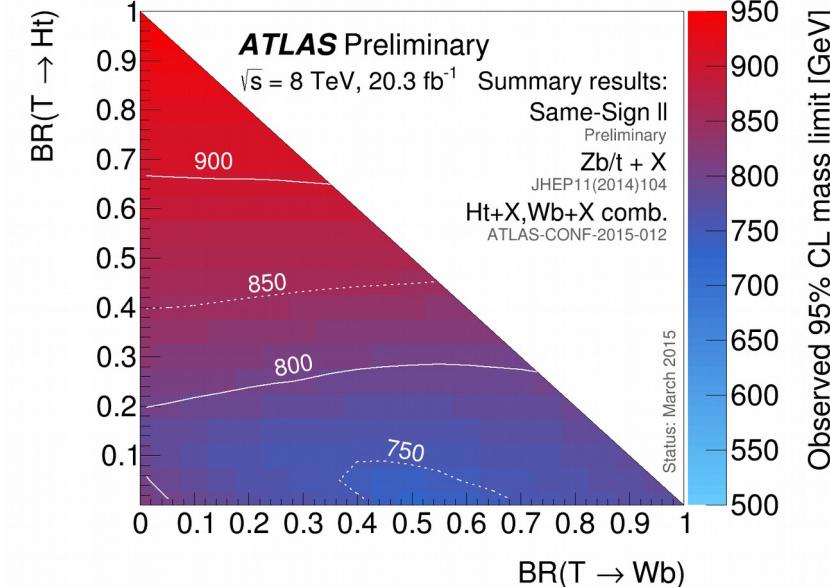


1503.05425 [hep-ex] **New!**

- Assuming allowable decay modes are:
 $B \rightarrow Wt/Zb/Hb$
- Consider subsets with 1 or more reconstructed hadronic boson
- Do not measure charge
 \rightarrow also set limits on $T_{5/3} \rightarrow Wt > 840\text{GeV}$

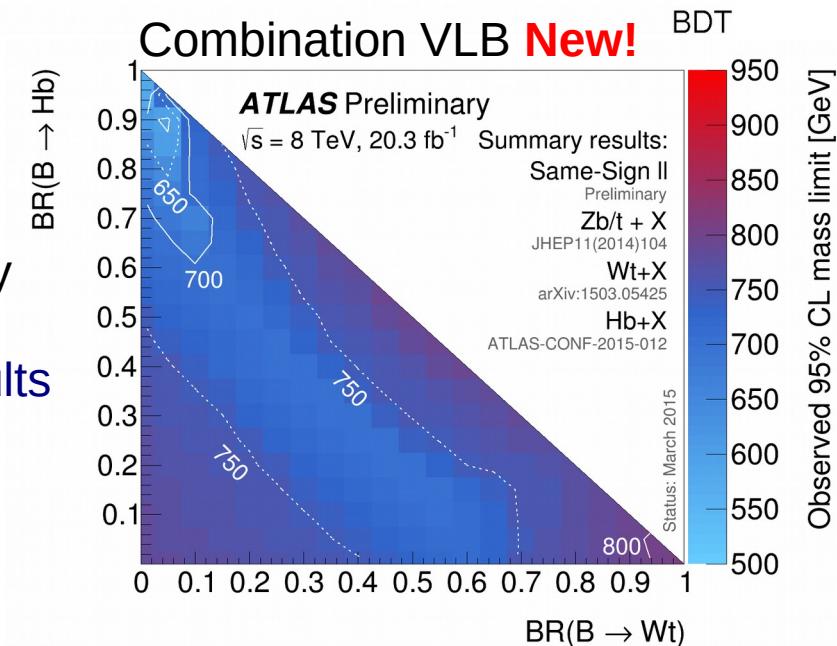


Combination VLT **New!**



For more summary plots, see the [ExoticsPublicResults](#)

Combination VLB **New!**





CMS: inclusive VLT & VLB

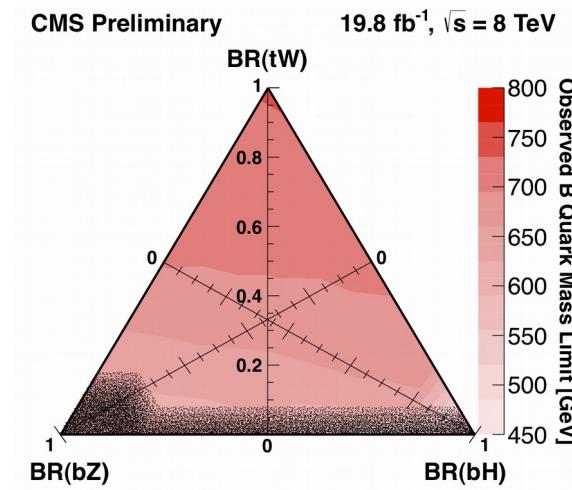
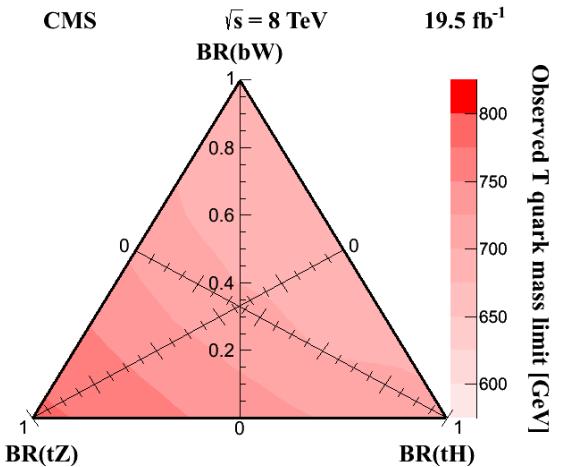
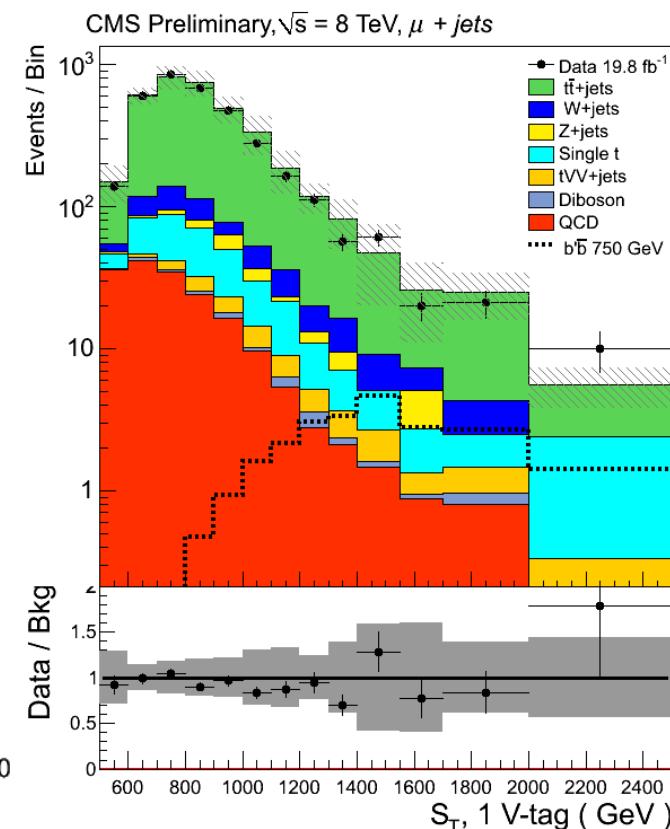
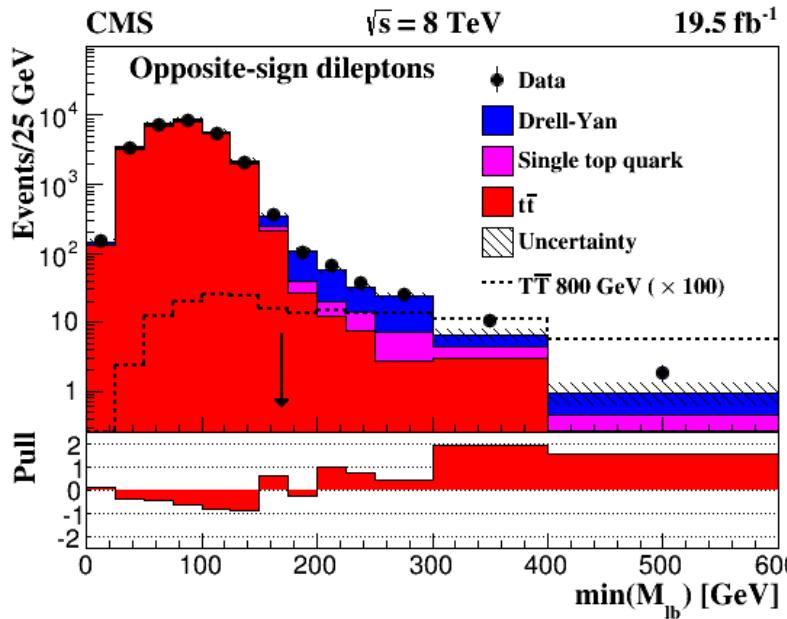
Comprehensive searches for $T\bar{T}$ and $B\bar{B}$ in:

Phys. Lett. B729 (2014) 149-171

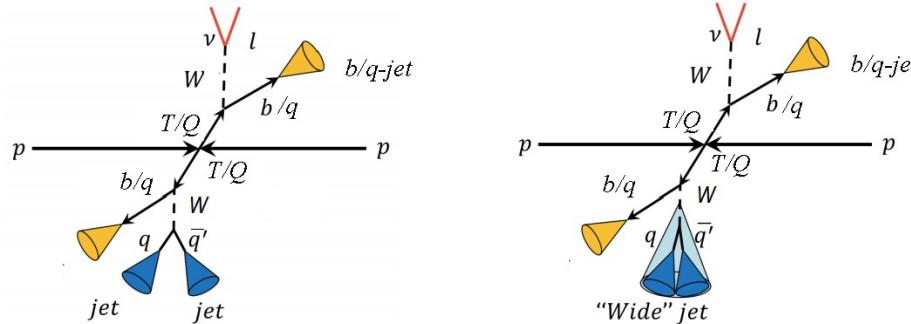
- Single lepton
- Multilepton
- Opposite-sign, on/off-Z
- Same-sign
- Trilepton

CMS-PAS-B2G-12-019

- Single lepton
- ≥ 4 jets, ≥ 1 b-jet
- 0, 1, $2 \geq$ V-tags



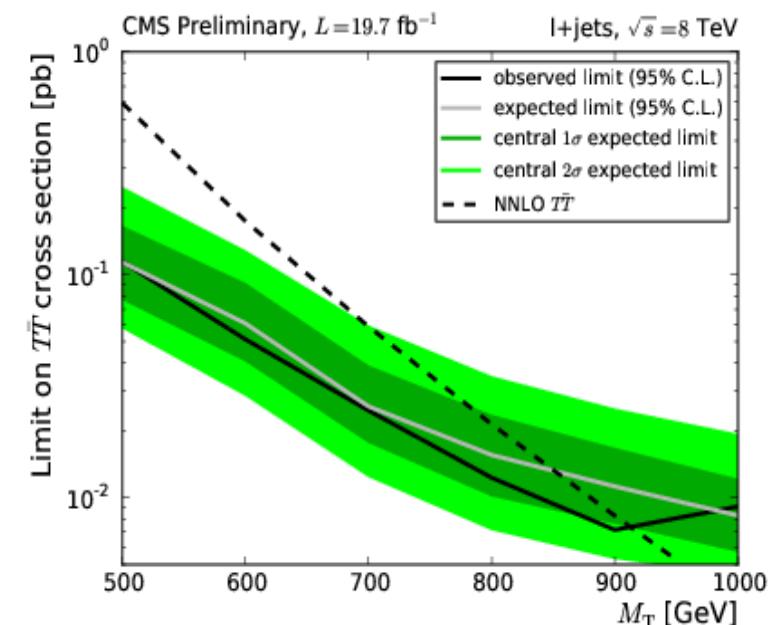
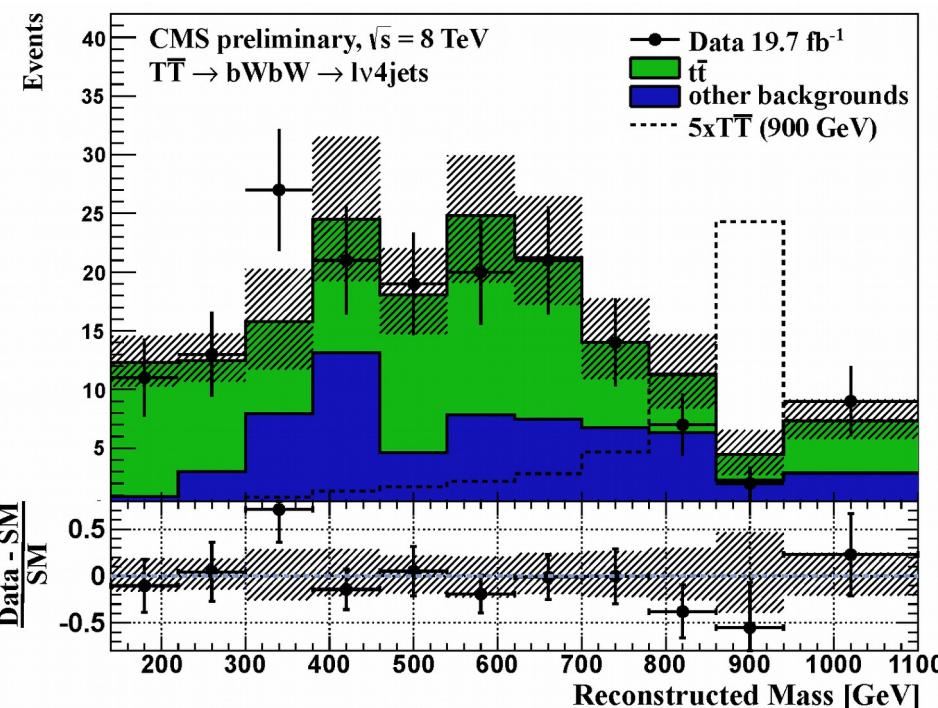
CMS: VLQ $\ell + \text{jets}$



New!

CMS-PAS-B2G-12-017

- Assume $\text{BR}(T \rightarrow Wb) = \text{BR}(Q \rightarrow Wq) = 100\%$
- For the hadronic W, consider both
 - resolved decay
 - boosted decay





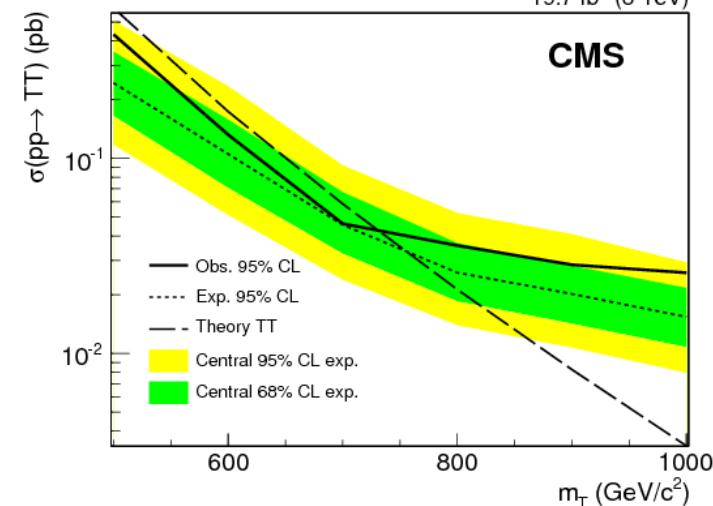
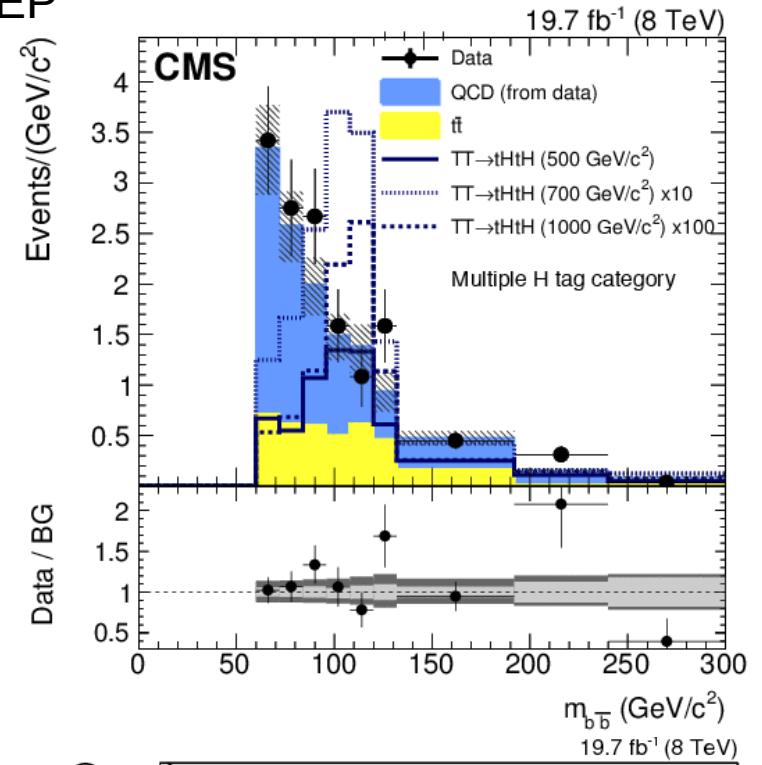
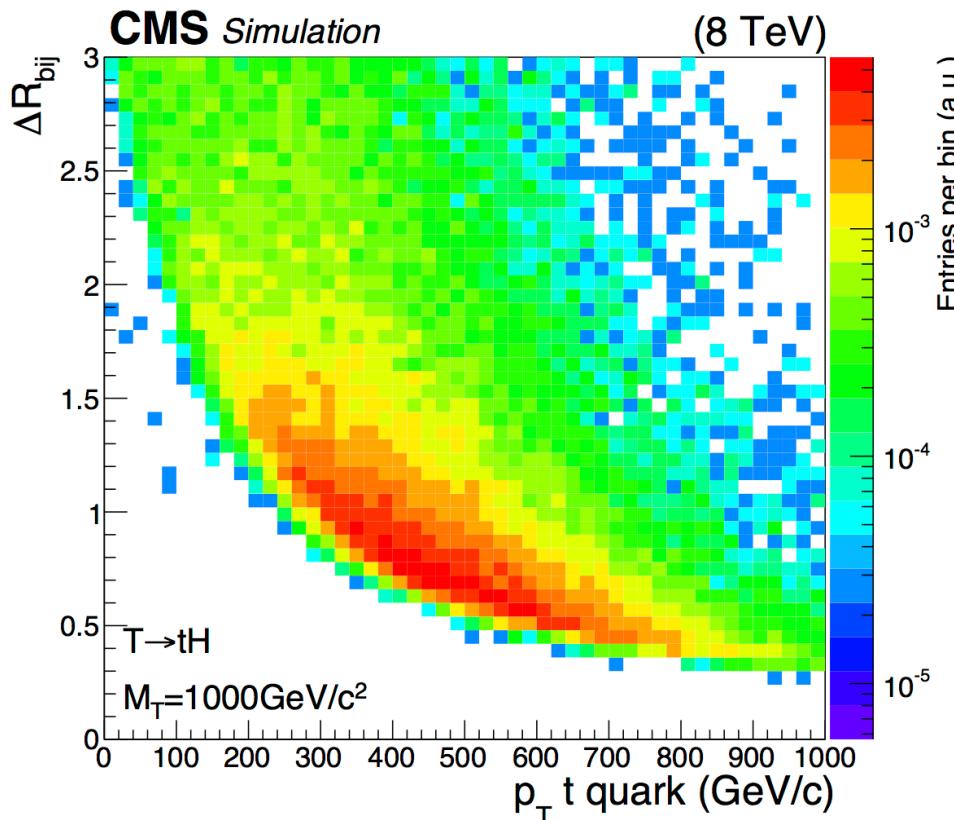
CMS: VLQ all-had



New! submitted to JHEP
1503.01952 [hep-ex]

- ≥ 2 high- p_T CA jets ($R=1.5$)
- ≥ 1 top candidate (HEP top tagger)
- ≥ 1 Higgs candidate

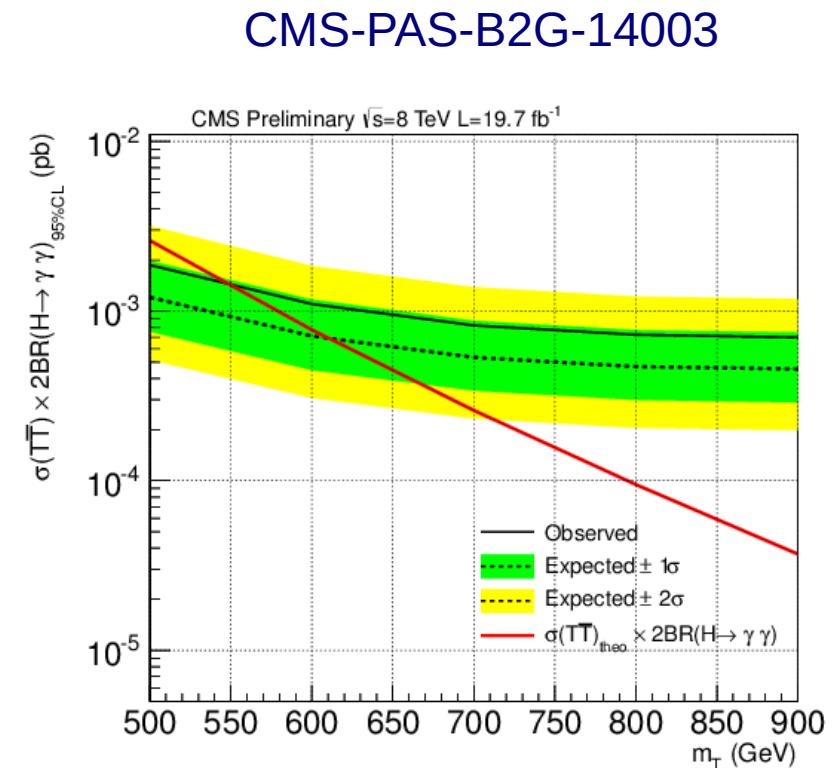
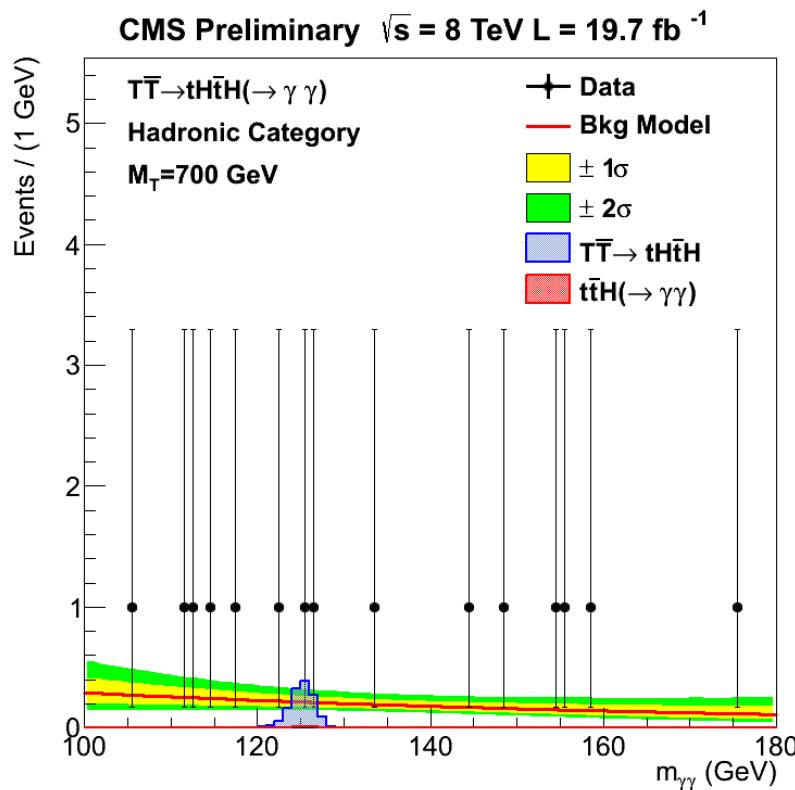
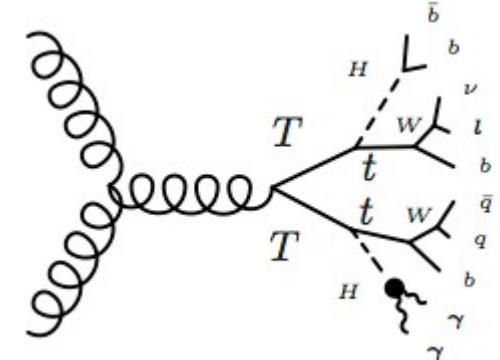
For the first time: tagging boosted Higgs with a combination of jet substructure and b-tagging.

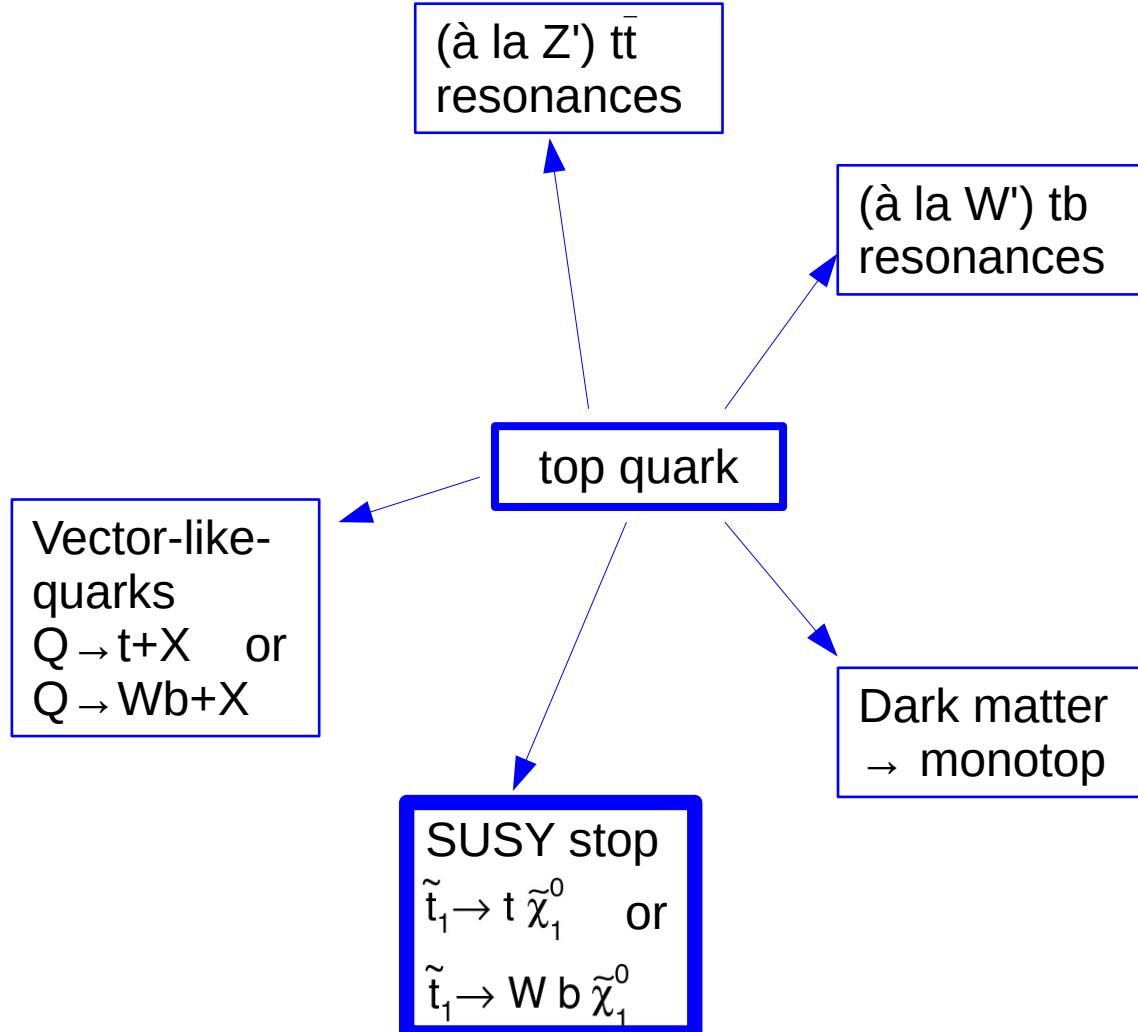




CMS: VLQ Ht+X, $H \rightarrow \gamma\gamma$

- One Higgs boson required to decay $H \rightarrow \gamma\gamma$
 - Low BR, high purity
 - Hadronic ($W \rightarrow qq$) and leptonic ($W \rightarrow \ell\nu$) channels
- Loose kinematic selection (H_T)





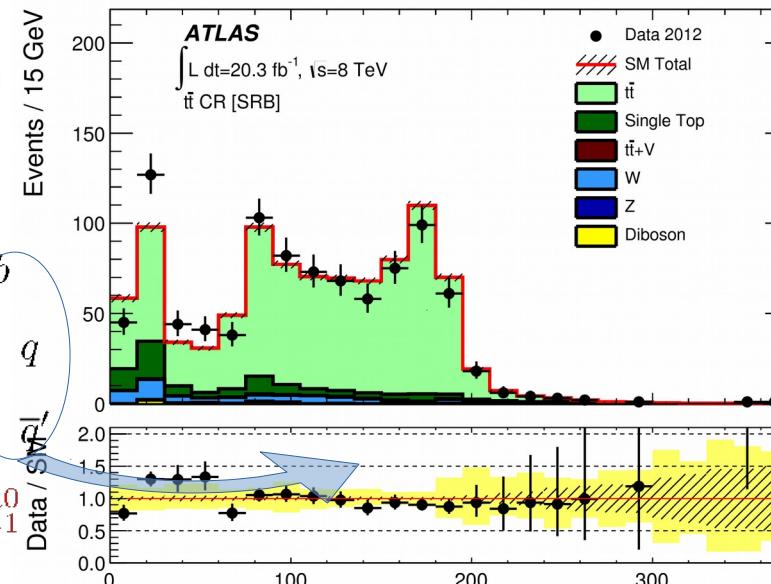
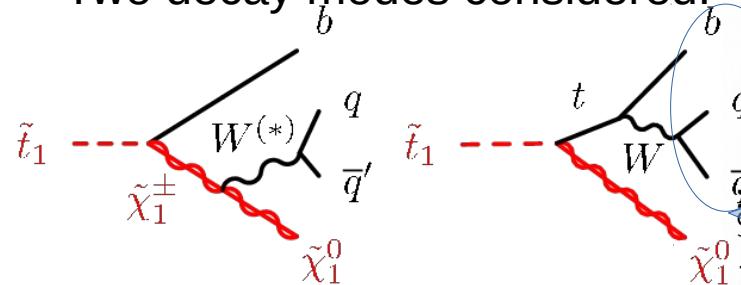


ATLAS: stop

Pair produced stop detected in **all-hadronic** top decays:

JHEP 09 (2014) 015

Two decay modes considered:



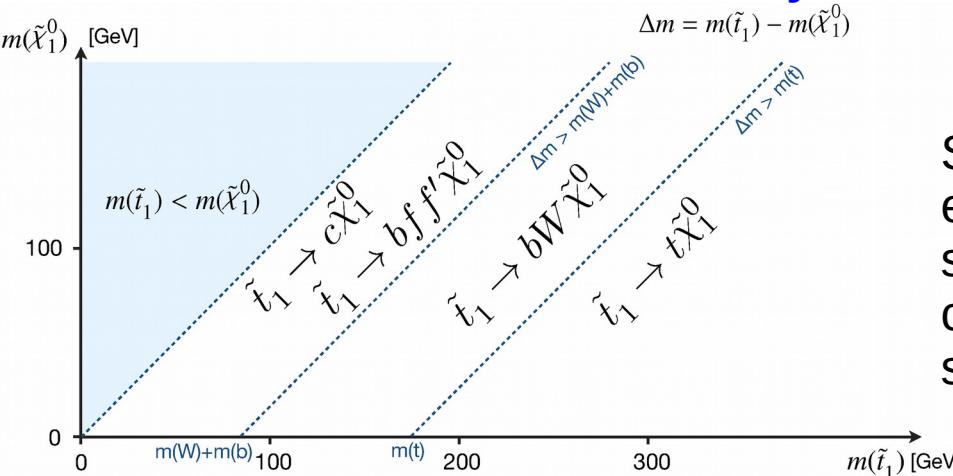
Three categories considered:

- fully resolved (6 jets)
- partially resolved (2 jets reclustered with R=1.2)
- five jets

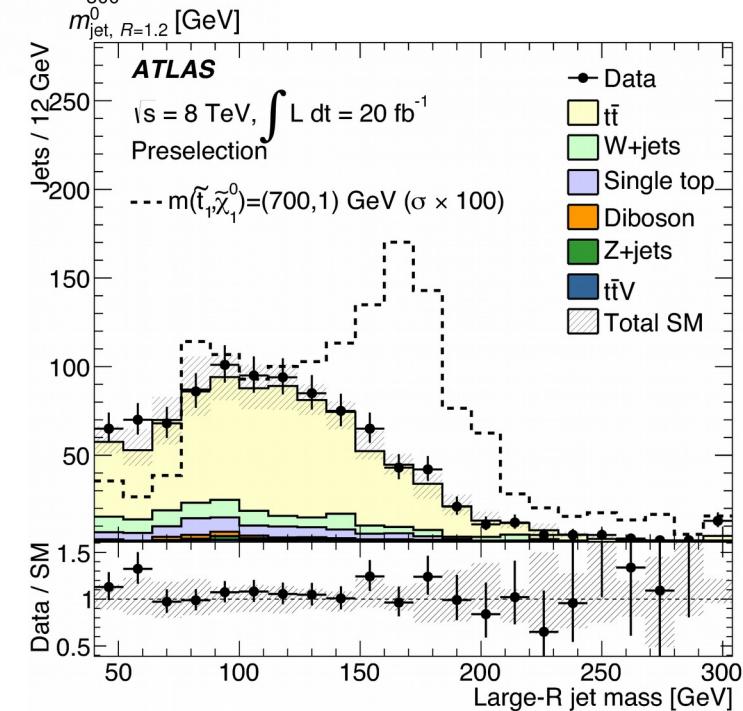
Most discriminating variable: missing E_T

Pair produced stop detected in **t+jets** top decays:
JHEP11(2014)118

Several signal regions accounting for different **mass hierarchies** and **decay modes**



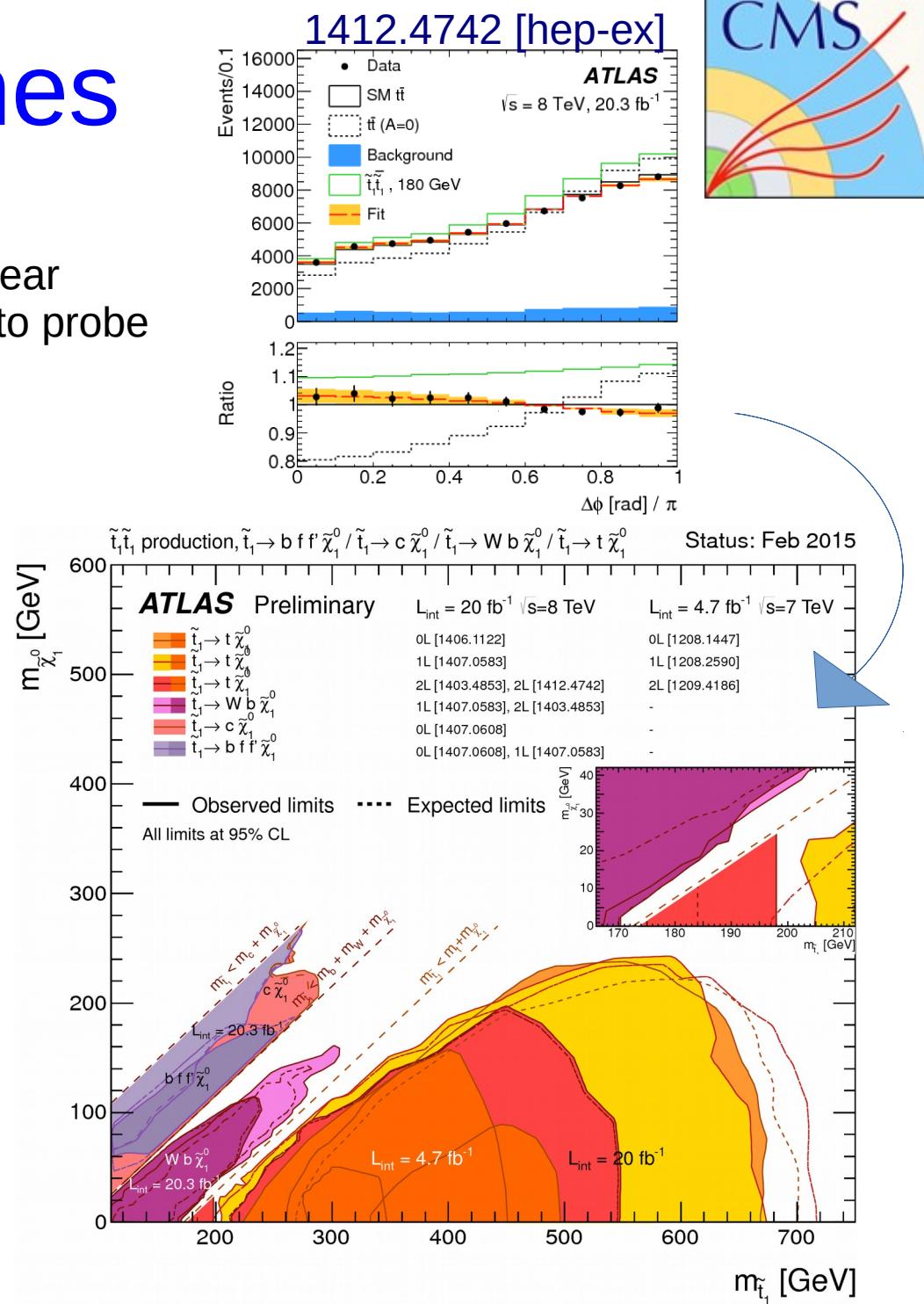
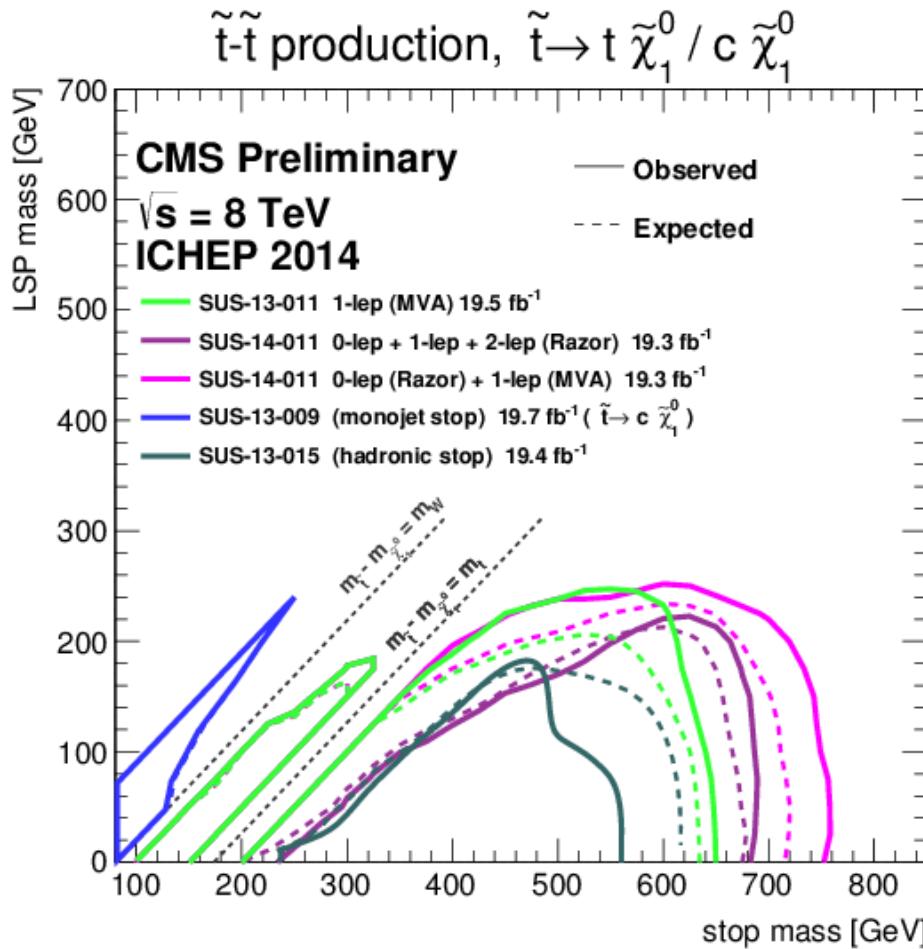
Shape fits enhance sensitivity in challenging scenarios



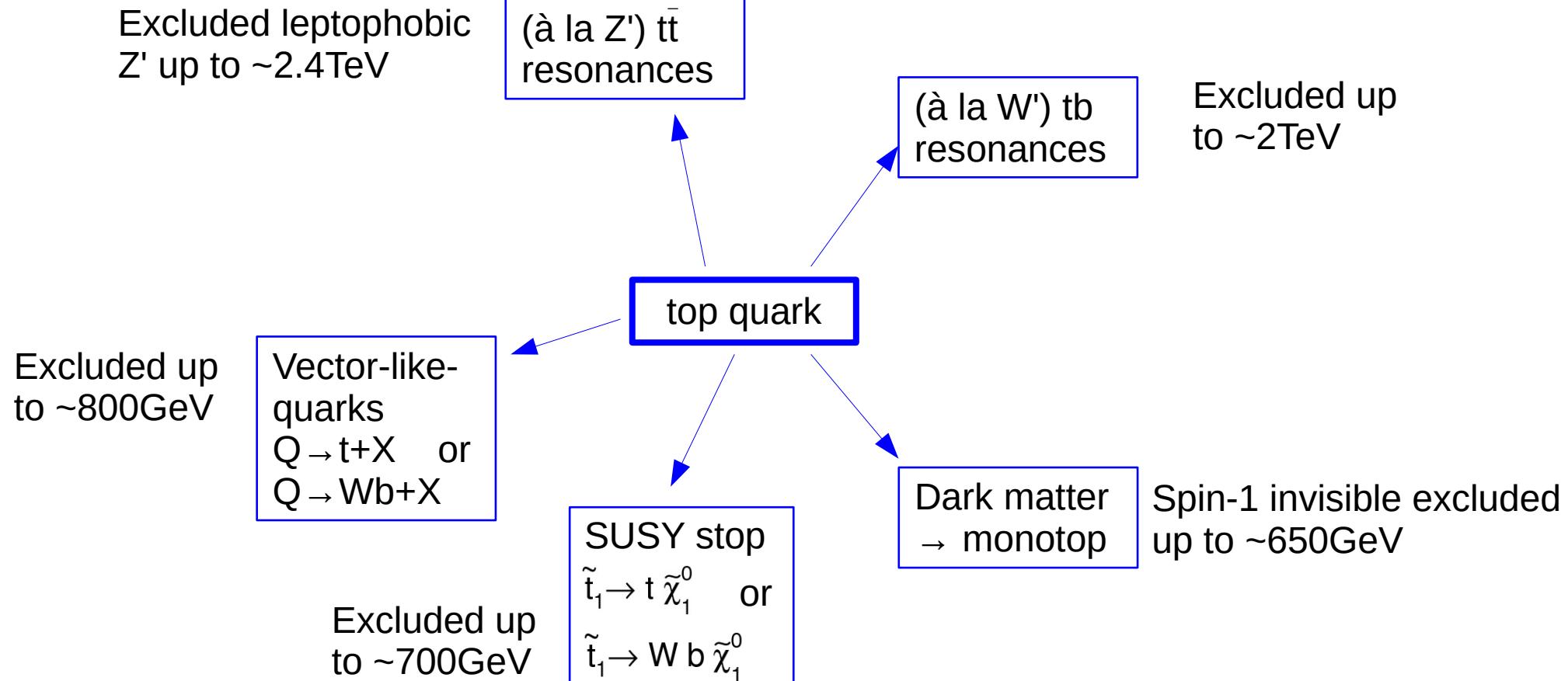


Stop Searches

Impressive coverage already reached last year
 Detailed $t\bar{t}$ measurements made it possible to probe
 the stealth stop region ($m_{\tilde{t}} \sim m_t$)
 → see yesterday's talk by Frederic Deliot



Outlook



- Top turns 20, and plays a **central role** in many searches for new physics at the LHC
- **New tools**, such as top tagging and reconstruction of boosted objects, are key in many of these searches
- Looking forward to the next 20 years of top physics; hopefully it will lead to the observation of new physics!

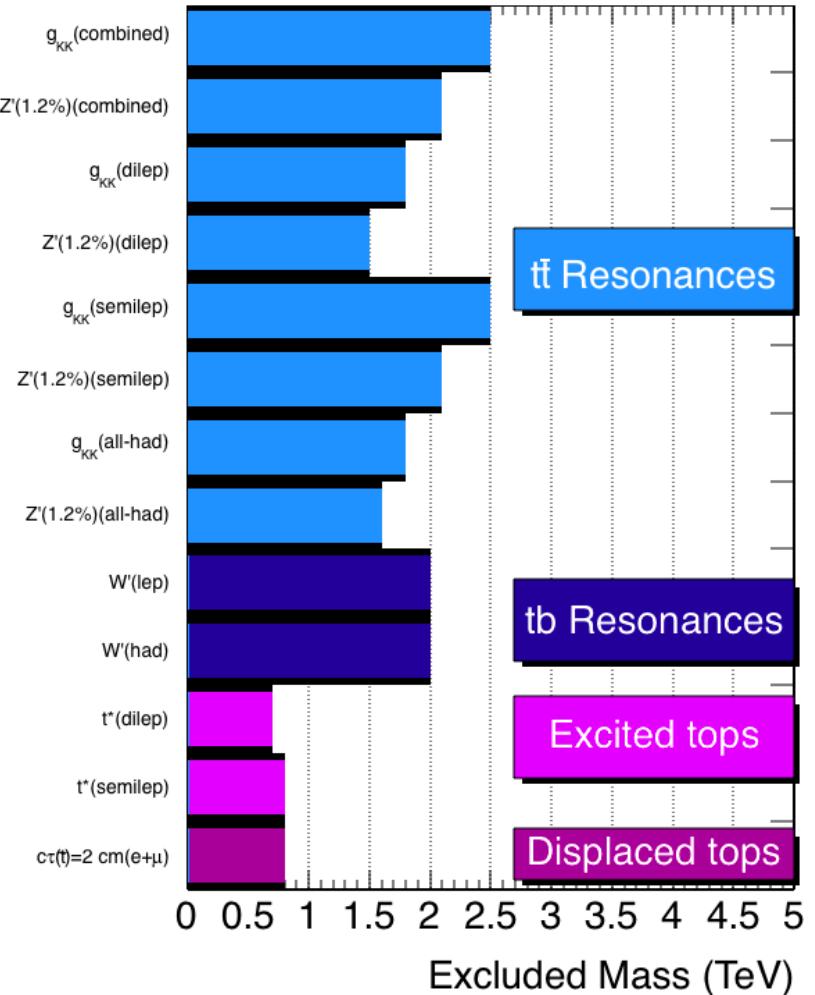
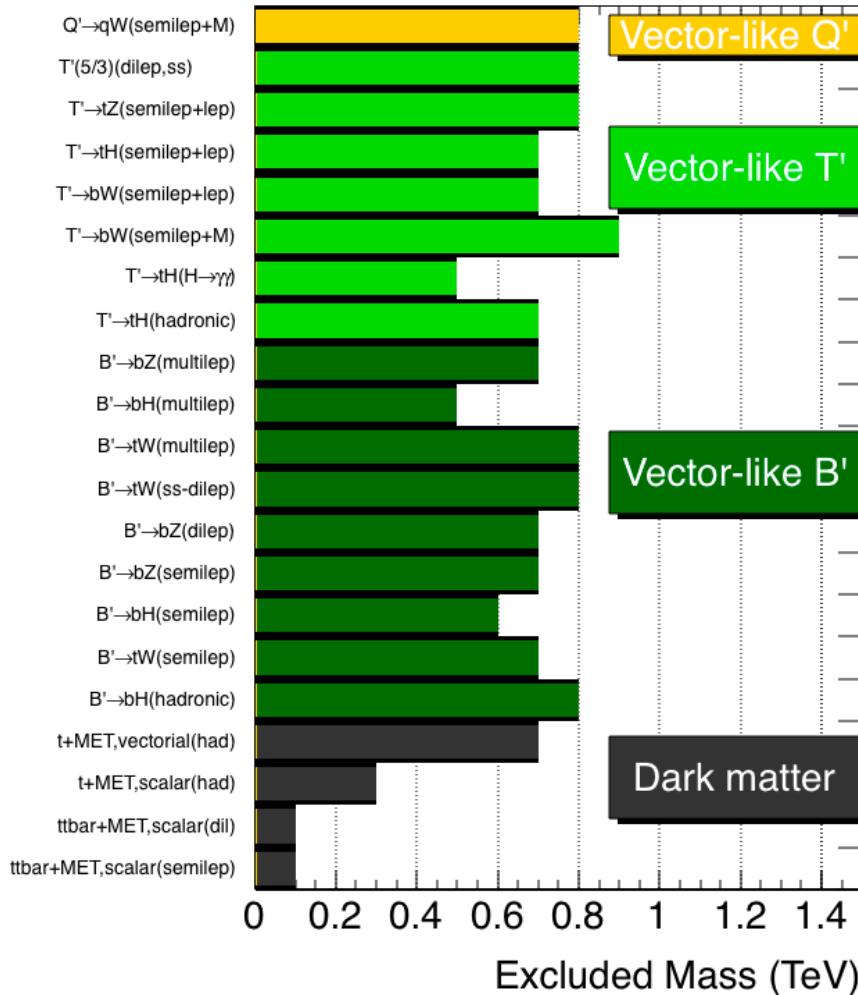


Extra



CMS B2G Summary

CMS Searches for New Physics Beyond Two Generations (B2G) 95% CL Exclusions (TeV)





ATLAS Exotics Summary

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$$\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 7, 8 \text{ TeV}$$

Reference

Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit		
Extra dimensions							
ADD $G_{KK} + g/q$	—	$\geq 1 j$	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
ADD non-resonant $\ell\ell$	$2e, \mu$	—	—	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
ADD QBH $\rightarrow \ell q$	$1 e, \mu$	$1 j$	—	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
ADD QBH	—	$2 j$	—	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
ADD BH high N_{trk}	2μ (SS)	—	—	20.3	M_{th} 4.7 TeV	$n = 6, M_D = 3 \text{ TeV}$, non-rot BH	1308.4075
ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	—	20.3	M_{th} 5.8 TeV	$n = 6, M_D = 3 \text{ TeV}$, non-rot BH	1405.4254
ADD BH high multijet	—	$\geq 2 j$	—	20.3	M_{th} 5.8 TeV	$n = 6, M_D = 3 \text{ TeV}$, non-rot BH	Preliminary
RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	—	—	20.3	G_{KK} mass 2.68 TeV	$k/\bar{M}_{Pl} = 0.1$	1405.4123
RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	—	—	20.3	G_{KK} mass 2.66 TeV	$k/\bar{M}_{Pl} = 0.1$	Preliminary
Bulk RS $G_{KK} \rightarrow ZZ \rightarrow q\bar{q}\ell\ell$	$2 e, \mu$	$2 j / 1 J$	—	20.3	Z' mass 740 GeV	$k/\bar{M}_{Pl} = 1.0$	1409.6190
Bulk RS $G_{KK} \rightarrow WW \rightarrow q\bar{q}\nu\nu$	$1 e, \mu$	$2 j / 1 J$	Yes	20.3	W' mass 700 GeV	$k/\bar{M}_{Pl} = 1.0$	1503.04677
Bulk RS $G_{KK} \rightarrow HH \rightarrow h\bar{h}h\bar{h}$	—	$4 b$	—	19.5	G_{KK} mass 590-710 GeV	$k/\bar{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
Bulk RS $g_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	20.3	g_{KK} mass 2.2 TeV	$BR = 0.925$	ATLAS-CONF-2015-009
2UED / RPP	$2 e, \mu$ (SS)	$\geq 1 b, \geq 1 j$	Yes	20.3	KK mass 960 GeV		Preliminary
Gauge bosons							
SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	—	—	20.3	Z' mass 2.9 TeV		1405.4123
SSM $Z' \rightarrow \tau\tau$	2τ	—	—	19.5	Z' mass 2.02 TeV		1502.07177
SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	—	Yes	20.3	W' mass 3.24 TeV		1407.7494
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3 e, \mu$	—	Yes	20.3	W' mass 1.52 TeV		1406.4456
EGM $W' \rightarrow WZ \rightarrow q\bar{q}\ell\ell$	$2 e, \mu$	$2 j / 1 J$	—	20.3	W' mass 1.59 TeV		1409.6190
HVT $W' \rightarrow WH \rightarrow \ell\nu bb$	$1 e, \mu$	$2 b$	Yes	20.3	W' mass 1.47 TeV	$gv = 1$	Preliminary
LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2 b, 0-1 j$	Yes	20.3	W' mass 1.92 TeV		1410.4103
LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	—	20.3	W' mass 1.76 TeV		1408.0886
CI							
CI $qqqq$	—	$2 j$	—	17.3	Λ 12.0 TeV $\eta_{LL} = -1$		Preliminary
CI $q\bar{q}\ell\ell$	$2 e, \mu$	—	—	20.3	Λ 21.6 TeV $\eta_{LL} = -1$		1407.2410
CI $u\bar{u}t\bar{t}$	$2 e, \mu$ (SS)	$\geq 1 b, \geq 1 j$	Yes	20.3	Λ 4.35 TeV $ C_{LL} = 1$		Preliminary
DM							
EFT D5 operator (Dirac)	$0 e, \mu$	$\geq 1 j$	Yes	20.3	M_* 974 GeV		at 90% CL for $m(\chi) < 100 \text{ GeV}$
EFT D9 operator (Dirac)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	20.3	M_* 2.4 TeV		at 90% CL for $m(\chi) < 100 \text{ GeV}$
LQ							
Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	—	1.0	LO mass 660 GeV	$\beta = 1$	1112.4928
Scalar LQ 2 nd gen	2μ	$\geq 2 j$	—	1.0	LO mass 685 GeV	$\beta = 1$	1203.3172
Scalar LQ 3 rd gen	$1 e, \mu, 1 \tau$	$1 b, 1 j$	—	4.7	LO mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks							
VLQ $TT \rightarrow Ht + X, Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
VLQ $TT \rightarrow Zt + X$	$2 \geq 3 e, \mu$	$\geq 2 \geq 1 b$	—	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
VLQ $BB \rightarrow Zb + X$	$2 \geq 3 e, \mu$	$\geq 2 \geq 1 b$	—	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
VLQ $BB \rightarrow Wt + X$	$1 e, \mu$	$\geq 1 b, \geq 5 j$	Yes	20.3	B mass 640 GeV	isospin singlet	Preliminary
$T_{5/3} \rightarrow Wt$	$1 e, \mu$	$\geq 1 b, \geq 5 j$	Yes	20.3	$T_{5/3}$ mass 840 GeV		Preliminary
Excited fermions							
Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	—	20.3	q^* mass 3.5 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1309.3230
Excited quark $q^* \rightarrow qg$	—	$2 j$	—	20.3	q^* mass 4.09 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1407.1376
Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	$1 b, 2 j$ or $1 j$	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
Excited lepton $\ell^* \rightarrow \ell\gamma$	$2 e, \mu, 1 \gamma$	—	—	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2 \text{ TeV}$	1308.1364
Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	$3 e, \mu, \tau$	—	—	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
Other							
LSTC $a_T \rightarrow Wy$	$1 e, \mu, 1 \gamma$	—	Yes	20.3	a_T mass 960 GeV		1407.8150
LRSM Majorana ν	$2 e, \mu$	$2 j$	—	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2 \text{ TeV}$, no mixing	1203.5420
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2 e, \mu$ (SS)	—	—	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\ell) = 1$	1412.0237
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	—	—	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $BR(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$\alpha_{\text{non-res}} = 0.2$	1410.5404
Multi-charged particles	—	—	—	20.3	multi-charged particle mass 785 GeV	DY production, $ q = 5e$	Preliminary
Magnetic monopoles	—	—	—	2.0	monopole mass 862 GeV	DY production, $ g = 1 g_D$	1207.6411

$\sqrt{s} = 7 \text{ TeV}$ $\sqrt{s} = 8 \text{ TeV}$

10⁻¹ 1 10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.